Disclaimer:

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

TITLE: **Nat**ional **Carb**on Sequestration Database and Geographic Information System (**NatCarb**)

Cooperative Agreement No.:	DE-FC26-00NT40936
Contractor Name and Address:	The University of Kansas Center for Research Inc.
Date of Report:	March 17, 2007
Award Date:	September 28, 2000
DOE Cost of Project:	$398,807 (Budget Year 5 – 12 months) July 1, 2005 – June 30, 2006 $387,987 (Budget Year 6 -12 months) July 1, 2006 – June 30, 2007
Principal Investigators:	Timothy R. Carr (Program Manager)
Project Manager:	Dawn Deel, NETL Morgantown, WV
Reporting Period:	January 1, 2006—December 31, 2006

TABLE OF CONTENTS

FIGURES

TABLES

FORWORD

This report summarizes a cooperate project involving many different organizations. The project operates as an adjunct of the US Department of Energy's Regional Carbon Sequestration Partnerships and includes 300+ state agencies, universities, and private companies, spanning 40 states, three Indian nations, and four Canadian provinces (http://www.netl.doe.gov/technologies/carbon_seq/partnerships/partnerships.html). As part of the characterization phase, the partnerships have accumulated a wealth of geographic and geological data and information relevant to validate and potentially deploy carbon sequestration technologies. The main goals of the Characterization Phase were to collect data on CO_2 sources and sinks and develop an intellectual infrastructure to support and enable future carbon sequestration field tests and deployments. The partnerships also sought to evaluate and determine which of the numerous sequestration approaches that have emerged in the last few years are best suited for specific regions of the country. In addition, the partners began studying possible regulations and infrastructure requirements that would be needed should climate science indicate that sequestration be deployed on a wide scale in the future.

Regional partners through **NatCarb** have created and maintain the only carbon sequestration portal for matching CO_2 sources with nearby sinks—geologic and terrestrial sequestration sites—in the United States and Canada. The **Nat**ional **Carb**on Sequestration Database and Geographic Information System (**NatCarb**) provides an Internet portal that brings together data from every partnership region into a network of regional carbon sequestration atlases for the United States, which were used to identify promising sequestration opportunities; and raise awareness and support for carbon sequestration as a greenhouse gas mitigation option, both within industry and the general public. The portal is updated regularly by region, and is available to decision makers and the general public through a single website (http://www.natcarb.org/).

ABSTRACT

This annual report describes progress in the sixth year of the multi-year project entitled ***"NATional CARBon Sequestration Database and Geographic Information System (NatCarb)"*** (http://www.natcarb.org). The original project assembled a consortium of five states (Indiana, Illinois, Kansas, Kentucky and Ohio) in the midcontinent of the United States (MIDCARB) to construct an online distributed Relational Database Management System (RDBMS) and Geographic Information System (GIS) covering aspects of carbon dioxide (CO_2) geologic sequestration. The **NatCarb** system links the GIS information of the Carbon Sequestration Regional Partnerships (http://www.netl.doe.gov/technologies/carbon_seq/partnerships/partnerships.html) into a coordinated regional database system consisting of datasets useful to industry, regulators and the public. The project includes access to national databases and GIS layers maintained by the **NatCarb** group (e.g., brine geochemistry) and publicly accessible servers (e.g., USGS, and Geography Network) into a single system where data is maintained and enhanced at the local level, but is accessed and assembled through a single Web portal to facilitate query, assembly, analysis and display. This project improves the flow of data across servers and increases the amount and quality of available digital data.

Highlights of progress include a more user-friendly **NatCarb Carbon Explorer. NatCarb Explorer,** a simplified Internet Map Server (IMS), is intended for decision makers and the general public who are not GIS experts. The **NatCarb Carbon Explorer** includes information on major CO_2 sources and potential geologic storage sites coupled with limited display and analysis capabilities. In addition, the data assembled in the **NatCarb Carbon Explorer** were used to construct maps of North American CO_2 sources and sinks for a hard-copy national atlas. Images and data are presented in a series of high-quality static graphic images and interactive online images. The maps contain an improved symbology that provides a larger number of classes of major stationary "point sources" of CO_2 emissions (i.e., breaking into classes such as power plants, refineries, gas processing, etc.), and improvement of the representation of potential sequestration sites.

The national group has continued to assemble water geochemistry data from national and regional data bases and has developed an improved set of capabilities for query, visualization and analysis. These visualization and analysis tools are available for aquifers at a national, regional or local scale.

NatCarb works in cooperation with the Carbon Sequestration Regional Partnerships to improve the quality and quantity of data pertinent to CO_2 emissions and potential sequestration volumes at a regional and state level.

The **NatCarb** project is a functional demonstration of distributed management of data systems that cross the boundaries between institutions and geographic areas. The **NatCarb** system addresses CO_2 sequestration and other natural resource issues from sources, sinks and transportation within a spatial database that can be queried online. Visualization of high quality and current data can assist decision makers by providing access to common sets of high quality data in a consistent manner.

EXECUTIVE SUMMARY

The ***Nat**ional **Carb**on Sequestration Database and Geographic Information System **(NatCarb)*** provides national coverage across the Regional CO_2 Partnerships. Currently, the partnerships cover 40 states, three Indian Nations and four Canadian provinces (Figure 1, http://www.natcarb.org). Advanced distributed computing solutions are used to link database servers across the partnerships and other publicly accessible servers (e.g., USGS, TerraServer) into a single system where data is maintained and enhanced at the local level, but is accessed and assembled through a single Web portal (Figures 2, 3). Information important to technical and policy decisions can be queried, assembled, analyzed and displayed. The **NatCarb** project has improved the flow of data across servers and increased the amount and quality of available carbon sequestration information at national, regional and local scales.

The online tools used in the project continue to improve in stability and speed in order to promote real-time display and analysis of CO_2 sequestration data. In past year, the continued move away from direct database access to web access through eXtensible Markup Language (XML) has increased stability and security, enhanced available capabilities, while decreasing management overhead. The software systems developed as part of the **NatCarb** project represent cutting edge approaches to constructing a national cyberinfrastructure for carbon management. The data assembled represents one of the most comprehensive data sets assembled to address questions of CO_2 sequestration.

Major improvements include a more user friendly **NatCarb Carbon Explorer** a simplified Internet Map Server (IMS) that is intended for decision makers and the general

public who are not GIS experts. The **NatCarb Carbon Explorer** includes information on major CO_2 sources and potential geologic storage sites coupled with limited display and analysis capabilities. In addition, the data assembled in the **NatCarb Carbon Explorer** were used to construct maps of North American CO_2 sources and sinks for a hard-copy national atlas. These images and data are presented as a series of high-quality static graphic images and interactive online images.

Enhancements have been made to the ability to display data from saline formations. The project has added to a significant database of aquifer geochemistry. The data consists of geographic location, stratigraphic unit, water geochemistry, temperature and depth for over 85,000 brine samples. The data consists primarily of standard water geochemistry (cations/anions), but there are samples that contain more esoteric data (e.g., isotopic values and organic species). At present **NatCarb** only displays the more traditional water analysis data. New tools have been developed to provide improvements in the query, display and analysis of brine geochemistry using a variety of online tools.

The **NatCarb** project is a functional demonstration of cyberinfrastructure as an effective federation of both distributed resources (data and facilities) and distributed multidisciplinary expertise (Regional CO_2 Partnerships). A National Carbon Cyberinfrastructure (NCCI) is required to assemble the large amounts of data in order to address the complex challenges of creating a continent-wide network of partnerships to determine the most suitable technologies, regulations, and infrastructure requirements for safe and efficient carbon capture, storage and sequestration in different areas (Figure 4). The **NatCarb** system addresses CO_2 sequestration and other natural resource issues from sources, sinks and transportation within a spatial database that can be queried online at

multiple scales from national to local (Figures 4-5). Visualization of high quality and up-to-date data related to CO_2 sequestration can assist decision makers.

GIS layers accessible through **NatCarb** provide access to millions of records at multiple scales from points to polygons (e.g., individual well bore or CO_2 source to saline aquifers across regions and states). Online data can be accessed, merged, queried, analyzed and displayed to fit the needs of the individual user. **NatCarb** has developed tools to select sequestration sites meeting multiple criteria (e.g., geographic location, depth, temperature, etc.) and estimate the volume of CO_2 that can be sequestered.

The **NatCarb** project has demonstrated what works and what doesn't when constructing large data systems that cover multiple institutions and require high-quality data at a range of scales.

For example –

- Each CO_2 Partnership varies in database and GIS resources, but all are now capable of constructing and linking GIS layers and databases to the **NatCarb** system.
- Each CO_2 Partnership is capable and motivated to serve large volumes of existing data relevant to CO_2 sequestration through the **NatCarb** system. **NatCarb** is more efficient and consistent than isolated servers focused on a single partnership.
- Some data are better served centrally. Example - It is more efficient to centrally process coal basin maps or digital orthophotos and serve them from a single location.

- National data that already exists (e.g., USGS Digital Elevation Model) can be accessed from remote servers not part of **NatCarb** and provided to the online user and to the individual CO_2 Partnership.
- Simple and flexible display and analysis tools (e.g., CO_2 emissions versus time plots) can be developed that can query and display data in real-time. These tools can be shared among the partnerships.
- **NatCarb** provides a demonstration of cyberinfrastructure as an integration of resources (data and facilities) and multidisciplinary expertise (Regional CO_2 Partnerships). The key remains a coordinated but distributed authority and management of the data by the institutions that own and maintain the data, wherever the data are located.

PROJECT OBJECTIVES

In the face of growing concerning over the consequences of anthropogenic release of carbon dioxide and other greenhouse gases (e.g., Wigley et al. 1996), increasing attention has been focused on the feasibility of large-scale capture and sequestration of carbon (e.g., Pacala and Socolow 2004). The United States and 189 nations ratified the 1992 United Nations Framework Convention on Climate Change, which states as its goal, "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UN 1992). One potential method to mitigating climate change is capture and storage of greenhouse gases (primarily CO_2). Carbon dioxide (CO_2) capture and storage (CCS) is a process consisting of the separation of CO_2 from industrial and energy-related sources, transport to a storage

location and long-term isolation from the atmosphere (IPPC 2005). The challenges to capture and store carbon on a sufficiently large scale and in a sufficiently timely manner present many challenges, technical, economic, political, and social.

Technical challenges include methods for industrial-scale capture of carbon dioxide prior to atmospheric release, methods for enhancing biological uptake of carbon dioxide and conversion to biomass, methods for transportation and injection of carbon dioxide in well bore-holes, methods for safely storing carbon belowground in geologic repositories and saline aquifers, and methods for measurement and monitoring of the movement of carbon (e.g., Eswaran et al. 1995; Edmonds et al. 2004; Lal 2004; IPCC 2005). Various treatments have addressed the economic, regulatory, and social aspects of large-scale carbon capture and sequestration (IOGCC 2005, IPCC 2005). Recent attention has turned to the challenge of collecting and making available disparate data (carbon sources, potential sinks, infrastructure, etc.) and analytical tools (pipeline measurement, carbon storage capacity estimation, cost estimation, brine geochemistry, etc.) required for addressing carbon capture and sequestration (Figure 6). While there is a growing body of research concerning data sharing (Goodchild et al. 2006) and the design of geoportals (Maguire and Longley 2005, Beaumont et al. 2005), much work is still needed both concerning technical design and long-term viability of geoportal implementation.

We extend the concept of *cyberinfrastructure,* first defined by the National Science Foundation (Atkins et al. 2003, Estin et al. 2003, and Berman and Brady 2005), to address carbon capture and storage. Cyberinfrastructure refers to an integrated computing environment that provides access to information, problem solving capabilities,

and communication (Atkins et al. 2003, Estin et al. 2003, and Berman and Brady 2005). A well-formulated cyberinfrastructure design, incorporating advances in informatics and geographic information systems (GIS), is essential for a national approach to carbon sequestration science and technology efforts.

Vision for National Carbon Cyberinfrastructure (NCCI): The challenges to a cyberinfrastructure can be stated as "the 3 C's" (Connection, Complexity and Coordination). The *connection* challenge arises with the attempt within an online environment to bring society together with the information and technology to formulate possible solutions. The *complexity* challenge centers on the challenges of managing, analyzing and visualizing within a geographic frame of extremely large and constantly evolving databases of diverse qualitative and quantitative data. The *coordination* challenge involves bringing together within a robust cyberinfrastructure multiple participating organizations and numerous dedicated and public-access server nodes.

The NatCarb vision for an NCCI consists of an online accessible and distributed computing environment that provides paths to the acquisition, storage and distribution of critical geospatial and tabular data from multiple sources including sensor networks and satellites, measurements from the field and experimental results, along with model simulations, and information services for search, visualization, and analysis (Figure 3). Geological sequestration data, focused on the assessment of large-scale geological sequestration, include measurements of potential storage volumes and the monitoring and verification of ongoing demonstration projects, such as those undertaken as part of the Carbon Sequestration Regional Partnerships, and efforts of other public and private entities. The data are gathered in centralized and participating data warehouses (Figure

4). Data are linked with online analysis, visualization, and modeling tools to form a *Knowledge Base*. Information is accessed and assembled through a single Web portal and provided to the decision-makers and the general public. In order to successfully design a successful NCCI, we must provide on-going reliable assess to a comprehensive set of data libraries, model simulations, and associated tools.

Evaluating the Success of Carbon Cyberinfrastructure: A successful NCCI will require comprehensive data libraries, together with model simulation libraries, and associated information services (search, visualization, and analysis tools) focused on the scientific, technical, environmental, economic, and social aspects of capture and storage of CO_2, with a sustainable design that links all NCCI elements. One key element involves provision for collection of data and simulation libraries in a *Knowledge Base*. Knowledge base data libraries must include up-to-date national information concerning carbon sources (atmospheric greenhouse gas emissions), potential terrestrial carbon sequestration sinks, potential geologic carbon sequestration sinks, and base geospatial data layers (political boundaries, topography land use/land cover, etc.) and infrastructure (roads, pipelines, etc.). Additional pilot implementation and economic data libraries must contain supporting field and analytical data and results of economic analyses. Information services must include map-based visualization capabilities together with key analysis tools, such as tools for calculating sequestration potential and optimal routes for CO_2 transport. In addition to their scientific and technical utility, the information, simulations, and tools within the NCCI could help to address legal and regulatory issues, public perception, environmental impacts and safety as well as issues related to inventories and accounting of greenhouse gas emission reductions. Data for

identification and assessment of sources and storage capacity represent an extremely large information universe involving diverse geospatial, tabular, and graphical data and will require a major effort in acquisition, processing, formatting, quality assurance, and preparation of metadata.

In order to construct the NCCI, management of key carbon sequestration data libraries, modeling libraries, and other resources (graphics, documents, etc.) contained in the National Carbon Atlas should be managed by distributed state and regional data managers in conjunction with national geoportal managers (Figures 3-4). The current *ad hoc* paths among the partnerships and between the partnerships and national portal for receipt of data and metadata streams from distributed data providers will need to be refined and further automated. A National Carbon Atlas Geoportal can improve data and metadata archiving, backup and updating. Maintenance of data and modeling library catalogs, including data and metadata status; coordination with data providers, other data managers, and geoportal managers; communication of feedback to data provider will need to receive increased attention.

Finally NCCI will require vision, technical leadership, management leadership and fiscal authority. Technical and management leadership to ensure that regional and national levels work together is critical. Effort will be required to provide management to ensure NCCI operates smoothly and achieves its goals. Fiscal sustainability of the NCCI, with allocation of funding for operation, update, and maintenance at all levels of organization should be considered a high priority.

The **NatCarb** project is a functional first-step demonstration of cyberinfrastructure as an effective federation of both distributed resources (data and facilities) and distributed multidisciplinary expertise (Regional CO_2 Partnerships). The system links together data from the Regional CO_2 Partnerships concerning sources, sinks and transportation within a spatial database that can be queried online. Information that addresses CO_2 sequestration is provided through a single interface that accesses the coverages and data from servers in each participating partnership and other servers providing national coverages. The **NatCarb** system is completely scalable and can be expanded to access, query and display CO_2 sequestration data on any accessible server at a participating site. **NatCarb** provides complete distributed management of the system (i.e., data and GIS layers can be edited and loaded from anywhere in the **NatCarb** system). The complexity and volume of data required to address CO_2 sequestration on a national and international basis rapidly increases the demands on any system to display the information, to integrate the data with models for analysis and to manage the system.

A distributed environment is required to address the complex challenges of creating a nationwide network of partnerships to bring the technical and policy expertise together with sufficient data to determine the most suitable technologies, regulations, and infrastructure for carbon capture, storage and sequestration in different areas. Access to high quality and up-to-date data related to CO_2 sequestration can assist decision makers by providing access to common sets of high quality data in a consistent manner in order to minimize the negative economic impact, and maximize the possible value of the CO_2 sequestration while addressing issues of heath safety and the environment (Figures 2-5).

PROJECT STATUS

The ***NAT****ional* ***CARB****on Sequestration Database and Geographic Information System* **(NatCarb)** provides an Internet portal that brings together data of the Carbon Sequestration Partnerships in a single convenient location. The portal is updated regularly by region, and is available to the general public through a single website (http://www.natcarb.org/). The architecture of the NatCarb system routes requests for an image of the data to and from the remote servers of the partnerships. The **NatCarb** system is built to work with ESRI Internet Map Services (ArcIMS) and Open Geospatial Consortium (OGC) Web Map Services (WMS). The remote servers contact their database and generate an image based on the request and send it back to the NatCarb server. **NatCarb** downloads, georeferences, and merges all of the remote layer images into a final layer that it sends to the client (Figure 3). This significantly reduces the quantity of data transmitted between servers as well as the amount of processing required at the **NatCarb** portal. Attribute data is requested from the remote servers only when a user specifically queries information from a layer. The transfer of attribute data is undertaken through web services using XML in place of direct query of remote databases. As a result of these architectural changes, the **NatCarb** system is robust, responsive, scalable, and secure.

The management overhead associated with the multiple layers across multiple servers in the **NatCarb** has been significantly reduced by moving to the new architecture. **NatCarb** has built a metadata repository of connection and layer information for each partner. This is a dynamic database that is managed with minimal central administration

by the individual partner administrators of the various servers. The remote administrators use an Internet web page that is served by **NatCarb** to enter the connection information for their own remote server. The **NatCarb** server automatically queries the distributed servers in order to locate all available layers. The remote administrator can then manage these layers remotely, indicating which layers the site should allow users to view, which columns should be displayed or queried and how to group the layers. Only the management information is stored on the **NatCarb** server in a relational database (Figure 3). All data processing is undertaken on the remote servers.

The **NatCarb** site has grown to serve a large number of data layers (>125), presentation and integration within the **NatCarb** viewer has become cluttered and overwhelming to the user. The graphical user interface (GUI) and the database and mapping requests component were redesigned so that layers could be grouped and displayed in a more organized fashion, and allow a simplified and more flexible design to be presented to the online user. In addition a new front end labeled the **National Carbon Explorer** was developed for the general public and non-technical user (Figures 6-10). The portal is built as two distinct components—the viewer, which is a graphical user interface (GUI), and the database and mapping requests component. The client GUI was built with Macromedia's Flash. Flash allows integration of text and graphics in a compact interface, and has the advantage of being self-contained inside the browser. This means that it does not matter which browser a client uses, only that they are using the current version of Flash (Macromedia reports that 97% of Internet-enabled desktops worldwide contain Flash). The Flash GUI handles the map layout, layer grouping, and tool grouping. Once the user selects a layer (or set of layers) from the *Layer List* to draw

and then zooms to an area, the Flash viewer communicates to a series of Macromedia ColdFusion MX (CFMX) backend pages that handle the viewer-database-IMS interaction. The CFMX pages dynamically build XML requests based on Flash parameters and the metadata database. These XML requests are sent to the remote servers that generate the maps or data requests. The resulting images are returned through the **NatCarb** server to the Flash client.

Our approach within **NatCarb** has been to assist the Regional Carbon Sequestration Partnerships to create and maintain carbon sequestration websites for matching CO_2 sources with nearby sinks—geologic and terrestrial sequestration sites—in the United States and Canada. In addition, **NatCarb** provides an Internet portal that brings together data from each partnership region into a single location. The individual regional and national data managers link regional or national data into **NatCarb**.

In **NatCarb**, work on developing display tools, and modeling and simulation components to display and manipulate data is at a very early stage. Examples include tools to query and display parameters such as brine geochemistry across multiple states, saline formations or other criteria (Figure 11A). Large amounts of data can be visualized with online tools using standard geochemical plots (e.g., Piper, Collins and Stiff diagrams). An early attempt at a simple model in **NatCarb** locates the least-cost path between any two points and generates a range of cost estimates for CO_2 pipeline transport (Zhang et al. 2006) (Figure 11B).

Web-database connectivity continues to improve among the Regional CO_2 Partnerships using Internet Map Server (IMS), eXtensible Markup Language (XML), and custom tools developed in JAVA, FLASH, and ColdFusion. **NatCarb** applications

access partnership and national databases for the analysis of both CO_2 sources and potential geologic sequestration sites. Software on numerous servers across the partnerships provides distributed processing for data analysis and display. Tools have been developed to provide complete distributed management of the system (i.e., data and GIS layers can be edited and loaded from anywhere in the **NatCarb** system). The software systems developed as part of the **NatCarb** project represent cutting edge approaches to online data access and management. The data assembled represents one of the most comprehensive data sets assembled to address questions of CO_2 sequestration.

Near-Term Strengths and Weaknesses of NatCarb: While it is possible with a reasonable level of accuracy to determine annual greenhouse gas (GHG) emission source data for most industrial sectors at a regional, national and state level, it is more difficult to examine monthly or daily emissions of individual point sources and predict the location of future GHG emission point sources (IPCC, 2005). In addition, an adequate resource assessment of storage capacity for individual sedimentary basins at the national and regional levels is required to establish existing opportunities for storing the CO_2. At the present time, **NatCarb** is neither comprehensive nor sufficient in coverage and structure to completely address carbon capture and storage at all levels from local to continent wide. Work is required to improve data and to provide tools to arrange data into areas that are amenable to policy solutions (e.g., state/province).

NatCarb is the latest version of an attempt to construct an NCCI. Initial versions used direct server-to-server query of remote databases and a single application server. The new **NatCarb** system architecture no longer communicates actual data, but an image of the data from the remote servers. This significantly reduces the quantity of data

transmitted between servers as well as the amount of processing required at the **NatCarb** portal. This has increased system performance, stability and security. The heterogeneous nature of the data across the North American continent and the independence of the Regional Carbon Sequestration Partnerships have resulted in geographic variations in the data layers. This is both a strength and weakness of the initial effort at construction of a NCCI. Strength in that different creative ideas and regional variations in carbon sources and sinks have resulted in widely different approaches. Weakness in that a consistent and reliable resource assessment of North American sequestration potential at the basin scale remains elusive. This continent-scale weakness is now being addressed through improved coordination across the partnerships and building consensus on the "best" approach to building a continent view, while maintaining regional "best" approaches.

The **NatCarb** portal requires a degree of GIS and relational database expertise that is not distributed across the entire technical community, and is not common among policy makers and the interested general public. This weakness is being approached by developing customized **NatCarb** portals that attempt to address the most pressing needs of different user communities. All portals will use the same underlying data, but provide more community focused views of carbon sequestration challenges and opportunities.

ACCOMPLISHMENTS

The ***Nat****ional* ***Carb****on Sequestration Database and Geographic Information System* **(NatCarb)** provides national coverage across the Regional CO_2 Partnerships. Currently, the partnerships cover 40 states, 3 Canadian provinces, and numerous organizations

(Figure 1; http://www.natcarb.org). In addition to providing access to data from the Regional CO_2 Partnerships, **NatCarb** provides national data for states not covered by a Regional Partnership (Figure 1). Advanced distributed computing solutions link database servers across the partnerships and other publicly accessible servers (e.g., USGS, TerraServer) into a single system where data is maintained and enhanced at the local level, but is accessed and assembled through a single Web portal. Information important to technical and policy decisions can be queried, assembled, analyzed and displayed. The **NatCarb** project has improved the flow of data across servers and increased the amount and quality of available carbon sequestration information at national, regional and local scales (Figures 2-5). The online tools used in the project have improved in stability and speed in order to provide real-time display and analysis of CO_2 sequestration data (Figure 6). The move away from direct database access to web access through eXtensible Markup Language (XML) has increased stability and security, while decreasing management overhead.

A major goal for 2006 was to construct a national coverage that provided a simplified view of CO_2 sources and potential geologic storage sites. This was accomplished through GIS layers covering "National CO_2 Facilities and Sinks" on the **NatCarb** website. Georeferenced information on large stationary sources of CO_2 was provided by each of the seven Regional Carbon Sequestration Partnerships (Figure 10). Each partnership collected data on a range of stationary sources and potential sinks. Data was provided on local servers but accessible by the **NatCarb** portal (e.g. Westcarb Atlas at http://www.westcarb.org/carbonatlas.htm). As represented in an online geographical information system (GIS), this data has a variable representation in terms of symbol

shape and color. As a default, the **NatCarb** portal represents all the CO_2 sources provided by the Regional Carbon Sequestration Partnerships and the National Group with a single symbology (Figure 5). The improved symbology provide a larger number of classes of major stationary "point sources" of CO_2 emissions (i.e., breaking into classes such as power plants, refineries, gas processing, etc.), and improvement of the representation of potential sequestration sites (Figure 10). In addition, for potential sequestration sites, such as oil and gas fields, coal beds and saline formations, where data is drawn from multiple partnerships, the symbology is also given a single color (Figure 12-14). All these modifications are undertaken in real-time as the layer is passed through the national portal (www.natcarb.org), and does not require the Regional Partnership to modify its representation of the source or potential sequestration site.

Saline formations represent an enormous potential for CO_2 storage capacity. However, less is known about saline formations than is known about hydrocarbon reservoirs and coal seams, and there is a greater amount of uncertainty associated with their amenability to CO_2 storage. Depending on the chemistry of the brine and the rock, CO_2 molecules can dissolve in brine or react with minerals to form solid mineral phases (e.g., carbonates). The carbonate reactions have the potential to be both a positive and a negative. The reactions can increase permanence, but they also may drastically reduce permeability of the formation and ability to inject CO_2 in the immediate vicinity of an injection well. The national group has assembled water geochemistry data from national and regional data bases and providing an improved set of capabilities for query, visualization and analysis (discussed below and Figures 15 and 16). These visualization and analysis tools are available for aquifers at a national, regional or local scale.

We are constantly working to improve the quantity and quality of the national databases that can supplement and enhance the work of the regional partnerships. As additional GIS layers begin to cross between regional partnerships, they will be represented at the national level with a consistent symbology, and supplemented with national data.

The **NatCarb** project is a functional demonstration of cyberinfrastructure as an effective federation of both distributed resources (data and facilities) and distributed multidisciplinary expertise (Regional CO_2 Partnerships). Such an environment is required to address the complex challenges of creating a nationwide network of partnerships to determine the most suitable technologies, regulations, and infrastructure requirements for safe and efficient carbon capture, storage and sequestration in different areas of the country. The **NatCarb** system addresses CO_2 sequestration and other natural resource issues from sources, sinks and transportation within a spatial database that can be queried online. Visualization of high quality and up-to-date data related to CO_2 sequestration can assist decision makers.

GIS layers and data tables accessible through **NatCarb** provide access to millions of records at multiple scales from points to polygons (e.g., individual well bore or CO_2 source to saline aquifers across regions and states, Figure 5). Online data can be accessed, merged, queried, analyzed and displayed to fit the needs of the individual user. **NatCarb** facilitates generation of custom images to fit the needs and scale required of the user (e.g., Figures 15, 17). **NatCarb** has developed tools to select sequestration sites meeting multiple criteria (e.g., geographic location, depth, temperature, etc.) and estimate the volume of CO_2 that can be sequestered.

The **NatCarb** project has demonstrated what works and what doesn't when constructing large data systems that cover multiple institutions and require high-quality data at a range of scales. For example –

- Each CO_2 Partnership and outside data sources (e.g., USGS) varies in database and GIS resources, but all are now capable of constructing and linking GIS layers and databases to the **NatCarb** system.
- Each CO_2 Partnership is capable of serving large volumes of existing data relevant to CO_2 sequestration through the **NatCarb** system. **NatCarb** is more efficient and consistent than isolated servers focused on a single partnership.
- Some data are better served centrally. Example - It is more efficient to centrally process coal basin maps or digital orthophotos and serve them from a single location.
- National data that already exists (e.g., USGS Digital Elevation Model) do not have to be reconstructed and can be accessed from remote servers not part of **NatCarb** and provided to the online user and to the individual CO_2 Partnership.
- Simple and flexible display and analysis tools (e.g., CO_2 emissions versus time plots) can be developed that can query and display data in real-time. These tools can be shared among the partnerships.
- **NatCarb** provides a demonstration of cyberinfrastructure as an integration of resources (data and facilities) and multidisciplinary expertise (Regional CO_2 Partnerships). The key remains a coordinated but distributed authority and management of the data by the institutions that own and maintain the data, wherever the data are located.

This report concentrates on selected major project accomplishments that occurred over calendar 2006, and where appropriate future work is highlighted. Major **NatCarb** project accomplishments are:

1) Continued to maintain a distributed project team and management that cross both institutional and technical boundaries. The pooling of subject domain and computing technical expertise has resulted in a product that could not be completed by any of the individual participating research institutions. The distributed team provides both interaction and innovation within a focused area. The project structure serves as a model for addressing other natural resource issues that cross boundaries among institutional and geographic entities. This team has been expanded to encompass personnel in each of the CO_2 Regional Partnerships.
2) The project has enhanced an online distributed system architecture that provides reliable communication and sharing among all the various servers of the **NatCarb** Consortium. The architecture incorporates open-platform methodologies that allow improved data sharing across servers, and incorporation of open GIS Consortium/Web Map Service map services. Use of spatial data engines and relational databases is not required. The interactive Web-based applications allow the Regional Partnerships in the **NatCarb** consortium to share, integrate, and display spatial data pertinent to CO_2 sources and geologic sequestration sites across the consortium states and provinces. Data remains local to be updated and

expanded. However, data is available for use in regional analysis and to increase the accessibility of this information to all interested parties.

3) **NatCarb Carbon Explorer** was constructed as a simplified Internet Map Server (IMS) that is intended for decision makers and the general public who are not GIS experts. The **NatCarb Carbon Explorer** includes information on major CO_2 sources and potential geologic storage sites coupled with limited display and analysis capabilities. In addition, the data assembled in the **NatCarb Carbon Explorer** were used to construct maps of North American CO_2 sources and sinks for a hard-copy national atlas. These images and data are presented as a series of high-quality static graphic images and interactive online images. Images can be customized to fit the scale and need of the user (Figures 15, 17)
4) In real-time, the **NatCarb** web portal transforms local data and provides a consistent symbology (color and shape) to the "National CO_2 Facilities" GIS layer on the **NatCarb** website and to common potential sequestration sites, such as oil and gas fields, where data is drawn from multiple partnerships, the symbology is also given a single color (Figures 10, 12-14). Data has been assembled covering the major sources and potential storage sites (Tables 1-4).
5) The project has generated and assembled a very large quantity of data elements pertaining to CO_2 sources and potential geologic sequestration sites. **NatCarb** has developed a significant database of aquifer geochemistry. The data consists of geographic location, stratigraphic unit, water geochemistry, temperature and depth for over 85,000 brine samples. The data consists primarily of standard water geochemistry (cations/anions), but there are samples that contain more

esoteric data (e.g., isotopic values and organic species) (Table 5). At present **NatCarb** only displays the more traditional water analysis data. The brine data can be queried as individual sample or group of samples in a number of ways that includes (Figures 2, 11, & 15):

a. Depth
b. State
c. Stratigraphic Unit
d. Oil or Gas Reservoir
e. Geographic Coordinates or Area

Procedures have been developed and automated to provide analysis and display tools that can be accessed directly or through the GIS layers. Improved tools allow clients to query and plot emissions through time for a single object to sum total emissions across an individual state, or group of sources. Additional tools allow the client to determine the estimated sequestration potential within a predetermined distance from an existing source or any other map location.

4) A major two-day workshop was undertaken in Lawrence, Kansas to develop methodologies to evaluate CO_2 sequestration volumes for major classes of potential geologic storage sites.

6) The project has improved an online distributed system for the management of the **NatCarb** system. Local site administrators for each of the consortium states have complete control to add or modify GIS layers and tables. All modifications and additions are online through the Internet from any facility. The complete distribution of site administration provides better management of components to

create a system that supports the distribution of high quality maps and GIS functionality on the Internet. It also provides the ability to scale the system for national coverage through the CO_2 Sequestration Partnerships and **NatCarb**.

7) We have provided technology transfer to the geologic and sequestration community and to the general public through talks, papers and posters (see Technology Transfer Section for a listing and examples).

Short-Term Goals: Immediate ongoing and short-term goals that will be realized prior to the end of the next project year are to:

1) Continue to work with the Regional CO_2 partnerships to expand GIS layers and databases to address sequestration on a national basis and to develop estimates of CO_2 emissions and potential storage volumes at state and regional level. Provide the initial data sets and GIS layers that can be used and enhanced by the partnerships. Add new GIS layers and databases that increase the richness of the **NatCarb** site. Assist in the expansion of coverage types in every state covered by the partnerships. Work to pioneer coverage and database types and spread the expertise to the other regions.
2) Continue to develop and add new and improved query and analysis tools. The biggest challenge remains to develop complex query and analysis capabilities that can be used to advance economic, technical, and environmental analysis of CO_2 sequestration potential at regional and state levels. Provide improved flexibility to designate scales of plots and displays. Provide improved download capabilities to move data and GIS layers to the client's machine for additional analysis. Work

with personnel from the Massachusetts Institute of Technology to integrate their advanced analysis tools into the **NatCarb** site.

3) Construct and demonstrate an efficient and useful national portal database to evaluate CO_2 sequestration potential at political levels such as the state/province. Work to bring all the partnerships and other interested parties into carbon sequestration information system coverage covering North America.
4) Construct a system that adequately presents data pertinent to terrestrial sequestration including forestry and agricultural sequestration.
5) Undertake a focused workshop to provide the technical expertise to develop a high quality Web-Enable Relational Database and GIS that covers the US for decision-makers, technical experts, and the general public. Address in workshop format the technical challenges of feedback to external data.
6) Provide a roadmap to maintain the NatCarb system beyond the end of the current project.

OVERVIEW OF TECHNICAL PROGRESS

A major challenge of the **NatCarb** project was to create an efficient, easy to access, and readily maintained knowledge management system with many millions of records pertaining to CO_2 sequestration that reside in multiple data warehouses across the Regional CO_2 Partnerships and other national sites (Figures 3, 4). The **NatCarb** system provides global access across the organizations to manipulate pertinent geologic and engineering data related to the issues involved in identifying and evaluating opportunities

for geologic CO_2 sequestration. Databases and GIS layers were developed in each state to characterize at multiple scales stationary sources of CO_2 and potential oil, gas, coal, and brine reservoirs for sequestration.

The **NatCarb** Consortium has developed and improved a distributed approach to knowledge management. Significant new tools and GIS layers have been added to the **NatCarb** system that enhances the ability to undertake economic, technical, and environmental analysis of CO_2 sequestration potential at regional and state levels. Derived GIS layers use estimate the quantity of CO_2 that could be sequestered under various physical conditions (e.g., temperature, pressure and salinity). The **NatCarb** system is one of the first distributed systems of natural resource data focused on CO_2 sources and potential geologic sequestration sites. Efforts remain underway to expand the **NatCarb** model through the Regional CO_2 Partnerships to provide improved national coverage.

PROJECT HIGHLIGHTS

The original MIDCARB consortium consisting of five states (Indiana, Illinois, Kansas, Kentucky and Ohio) constructed an online distributed Relational Database Management System (RDBMS) and Geographic Information System (GIS) covering aspects of carbon dioxide geologic sequestration (http://www.midcarb.org). That system linked the five states in the consortium through a coordinated regional database system consisting of GIS layers and datasets useful to industry, regulators and the public. The MIDCARB model was expanded as part of the **NatCarb** effort through development of coordinated working

relationships and assistance to the GIS efforts of the seven Regional CO_2 Partnerships. For **NatCarb**, the overall project organization is provided through the University of Kansas. Budgetary items are run through the Kansas University Center for Research (KUCR) and overall project coordination is provided through the Kansas Geological Survey.

The **NatCarb** project organization is unique in that it is distributive, geographic and overlapping. The organization is structured along both geographic boundaries and broad functions. The geographic focus of the Regional CO_2 Partnerships provides strong local expertise to characterize both CO_2 sources and potential geologic sequestration targets. The distributive focus provides a critical mass of technical people. A strong technical computing team was developed across institutional boundaries and has developed unique hardware and software solutions. This computing group pools technical expertise from each institution to work collaboratively on issues that are on the edge of distributed computing. No one institution has the technical computing expertise to create and maintain a system such as **NatCarb**. The technical computing leads keep the institutional management informed, and also interact closely with the individuals working on technical information concerning CO_2 sources and potential geologic sequestration sites (i.e., domain knowledge). The interaction between computing and domain teams at the local level provided unique solutions to address challenges and advanced both areas. The flexibility provided by the distributive structure of the **NatCarb** system allows for local experiments in data type, structure and display. Successful “experiments” can be propagated across the Regional CO_2 Partnerships.

Interaction between domain and computing technical experts within individual institutions and across institutions is on a daily basis. This is monitored through the local institutional leads and shared through email and through periodic phone conferences of the GIS working group of the Regional CO_2 Partnerships. Project integration is to a significant degree organic, in that all information has the same geographic structure, and has a similar look and feel.

CO_2 Sources

In 2004, total U.S. greenhouse gas emissions were estimated at 7,074.4 million metric tons CO_2 equivalent and include CO_2 and other greenhouse gases (e.g., CH_4, N_2O, and HFC's) (US EPA, 2006). The primary greenhouse gas emitted by human activities in the United States was CO_2 and totaled 5,988 million metric tons. CO_2 emissions result mostly from energy use and industrial processes (e.g., iron and steel and cement). These emissions are driven largely by economic growth, fuel used for transportation and electricity generation, and weather patterns affecting heating and cooling needs. In 2004, carbon dioxide emissions, related to the transportation sector were 1860.2 million metric tons. This results in a total of approximately 4,128 million metric tons of CO_2 emissions from stationary sources.

While not all potential stationary greenhouse gas sources have been examined, NatCarb in cooperation with NETL's Carbon Sequestration Partnerships have documented the location of more than 4,365 stationary sources with total emissions of 3,809 million metric tons of CO_2 (Table 1). Included are sources such as ethanol plants that are not included in inventories of greenhouse gasses. However, these sources are

important in that they produce high quality CO_2 from plant material and can be used to offset emissions from the combustion of fossil fuels.

Table 1 - CO_2 Sources Documented by Partnerships		
	Quantity (Million Tonnes)	**Number of Facilities**
PCOOR	401	1,037
Illinois Basin	343	212
Midwest	1,319	496
Southeast	1,021	981
WestCarb	132	62
Southwest	336	432
Big Sky	112	158
Northeast[1]	144	987
Total	3,809	4,365

Table 1. Estimated CO_2 emissions and sources evaluated by the Carbon Sequestration Partnerships and assembled through NatCarb. See Figure 10 for distribution of sources evaluated.

Oil and Gas Reservoirs

Depleted oil and gas reservoirs are formations that held crude oil and natural gas over millions of years. In general they are a layer of porous rock with a layer of non-porous rock above such that the non-porous layer forms a trap for the hydrocarbons. This same geometry offers great potential to trap CO_2 and makes these formations excellent sequestration opportunities. As a value-added benefit, CO_2 injected into a depleting oil reservoir can enable incremental oil to be recovered. NatCarb in cooperation with NETL's Carbon Sequestration Partnerships have documented at the various levels from state to reservoir more than 60 Giga metric tons of potential sequestration potential in depleted oil and gas reservoirs (Table 2).

Table 2 - CO_2 Storage - Oil & Gas Reservoirs (Giga Tonnes)		
	Low	**High**
PCOOR	19.6	19.6
Illinois basin	0.44	0.44
Midwest	2.5	2.5
Southeast	32.4	32.4
WestCarb	5.3	5.3
Southwest	1.0	1.6
Big Sky	0.75	0.75
Total	62	63

Table 2. Estimated low and high potential for CO_2 storage for oil and gas fields in basins evaluated by the Carbon Sequestration Partnerships and assembled through NatCarb. See Figure 12 for distribution of basins evaluated.

Unmineable Coal Seams

Unmineable coal seams are too deep or too thin to be mined economically. All coals have varying amounts of methane adsorbed onto pore surfaces, and wells can be drilled into unmineable coal beds to recover this coal bed methane (CBM). Initial CBM recovery methods, dewatering and depressurization, leave a fair amount of CBM in the reservoir. CO_2 preferentially adsorbs onto the surface of the coal, releasing the methane. Two or three molecules of CO_2 are adsorbed for each molecule of methane released, providing an excellent storage sink for CO_2. The maximum domestic capacity for CO_2 enhanced coalbed methane (ECBM) has been estimated at 90 billion metric tons CO_2, 40 billion metric tons of which are in Alaska (Reeves, 2003). Like depleting oil reservoirs, unmineable coal beds are a good early opportunity for CO_2 storage. NatCarb in cooperation with NETL's Carbon Sequestration Partnerships have documented at the basin level more than 60 to almost 100 Giga metric tons of potential sequestration potential in unmineable coal seams (Table 3).

Table 3 - CO_2 Storage – Unmineable Coal (Giga Tonnes)		
Sequestration Partnership	**Low**	**High**
PCOOR	8	8
Illinois basin	2.3	3.3
Midwest	0.9	0.9
Southeast	57.4	82.1
WestCarb	0	0
Southwest	0.85	2.3
Big Sky	0	0
Total	69.5	96.6

Table 3. Estimated low and high potential for CO_2 storage for deep unmineable coals in coal basins evaluated by the Carbon Sequestration Partnerships and assembled through NatCarb. See Figure 13 for distribution of basins evaluated.

Saline Formations

Saline formations are layers of porous rock that are saturated with brine. They are much more commonplace than coal seams or oil and gas bearing rock, and represent an enormous potential for CO_2 storage capacity. However, much less is known about saline formations than is known about crude oil reservoirs and coal seams and there is a greater amount of uncertainty associated with their amenability to CO_2 storage. Results indicate a large and variably distributed North American sequestration capacity of at least 3,620 gigatonnes (Gt) of carbon dioxide within deep saline formations (Dooley 2006).

Over the past year, **NatCarb** in cooperation with NETL's Carbon Sequestration Partnerships have documented the geographic distribution at the basin level of 1,000 to more than 3,223 Giga metric tons of potential sequestration potential in saline formations (Table 4).

In addition NatCarb has continued to develop a database of aquifer geochemistry. The data consists of geographic location, stratigraphic unit, water geochemistry,

temperature and depth for over 85,000 water samples (Table 5). The data consists primarily of standard water geochemistry (cations/anions), but there are samples that contain more esoteric data (e.g., isotopic values and organic species).

The brine data can be queried as individual sample or group of samples in a number of ways that includes:

- Depth
- State
- Stratigraphic Unit
- Oil and Gas Reservoir
- Geographic Coordinates or Area

The data can be displayed in map view (Figures 7, 8, 13), tables of groups of samples from selected saline formations, individual samples, or displayed with various graphical tools (e.g., Piper, Stiff or Concentration 10, 12, 14, 15). The system provides the user the ability to examine the geographic distribution, physical characteristics and chemistry of saline aquifers anywhere in North America. All data can be downloaded or displayed online. We have improved the analysis tools to handle samples across multiple states or formations.

Table 4 - CO_2 Storage - Saline Formations (Giga Tonnes)		
Sequestration Partnership	**Low**	**High**
PCOOR	97	97
Illinois basin	29	115
Midwest	118	118
Southeast	360	1,440
WestCarb	76	304
Southwest	18	64
Big Sky	271	1,085
Total	969	3,223

Table 4. Estimated low and high potential for CO_2 storage for brine formations in basins evaluated by the Carbon Sequestration Partnerships and assembled through NatCarb. See Figure 14 for distribution of basins evaluated.

KID (sample identification #)
STATE_CODE
COUNTY_CODE
FIELD_NAME
FIELD_CODE
LEASE_NAME
WELL_NAME
OPERATOR_NAME
LATITUDE
LONGITUDE
LONGITUDE_LATITUDE_SOURCE
TOWNSHIP
TOWNSHIP_DIRECTION
RANGE
RANGE_DIRECTION
SECTION
SUBDIVISION_1_LARGEST
SUBDIVISION_2
SUBDIVISION_3
SUBDIVISION_4_SMALLEST
SPOT
FEET_NORTH_FROM_REFERENCE
FEET_EAST_FROM_REFERENCE
REFERENCE_CORNER
DEPTH_TOP
DEPTH_BASE
DATA_SOURCE

SAMPLE_DATE
UPDATE_INITIALS
UPDATE_DATE
API_NUMBER
COMMENTS
ELEVATION_KB
ELEVATION_GL
ELEVATION_DF
ELEVATION_TGT
WELL_HEADER_KID_ORIGINAL
WELL_HEADER_KID
FORMATION
FORMATION_OLD
FORMATION_STRAT_KID
BICARBONATE
BROMINE
CALCIUM
CARBONATE
CHLORIDE
HYDROGEN_SULFIDE
IODINE
IRON
MAGNESIUM
SODIUM
SODIUM_OR_POTASSIUM
SULFATE
POTASSIUM

STRONTIUM
SPECIFIC_GRAVITY
SPECIFIC_CONDUCTIVITY
PH
RESISTIVITY_TEMPERATURE_F
RESISTIVITY
RESISTIVITY_AT_75
RESISTIVITY_ESTIMATE
FIELD_FLAG
GEOLOGIC_BASIN
USGS_PROVINCE
SINGLE_OR_MIXED_FORMATIONS
REVISED_SAMPLING_METHOD
CONCENTRATION_UNITS
CHARGE_BALANCE
MASS_BALANCE
LABORATORY
LONGITUDE_LATITUDE_RELIABILITY
DATA_SOURCE_URL
COMPLETION_DATE
FORMATION_AGE
CITATION
TOTAL_DISSOLVED_SOLIDS
UPLOAD_FILE_KID
ALUMINUM
AMMONIA
ANTIMONY
ARSENIC
BARIUM
BERYLLIUM
BISULFATE
BORON
BROMATE
CADMIUM
CHLORITE
CHLORATE
CHROMIUM

COBALT
COPPER
CYANIDE
FLUORIDE
HYDROXIDE
HYPOCHLORITE
LEAD
MANGANESE
MERCURY
MOLYBDENUM
NICKEL
NITRITE
NITRATE
PERCHLORATE
PHOSPHATE
SELENIUM
SILVER
THALLIUM
THORIUM
VANADIUM
ZINC
LITHIUM
RUBIDIUM
SILICA
DEUTRIUM_DELTA
DEUTRIUM_DELTA_UNITS
OXYGEN_18_DELTA
OXYGEN_18_DELTA_UNITS
STRONTIUM_87_86_DELTA
CONDUCTIVITY
CONDUCTIVITY_TEMPERATURE_F
PH_TEMPERATURE_F
SPECIFIC_GRAVITY_TEMPERATURE_F
ALKALINITY
CARBON_DIOXIDE
OXYGEN

Table 5. List of the data columns (variables) for samples in the NatCarb brine table. Not all the columns are full, but most of the major cations and anions are available for the majority of samples.

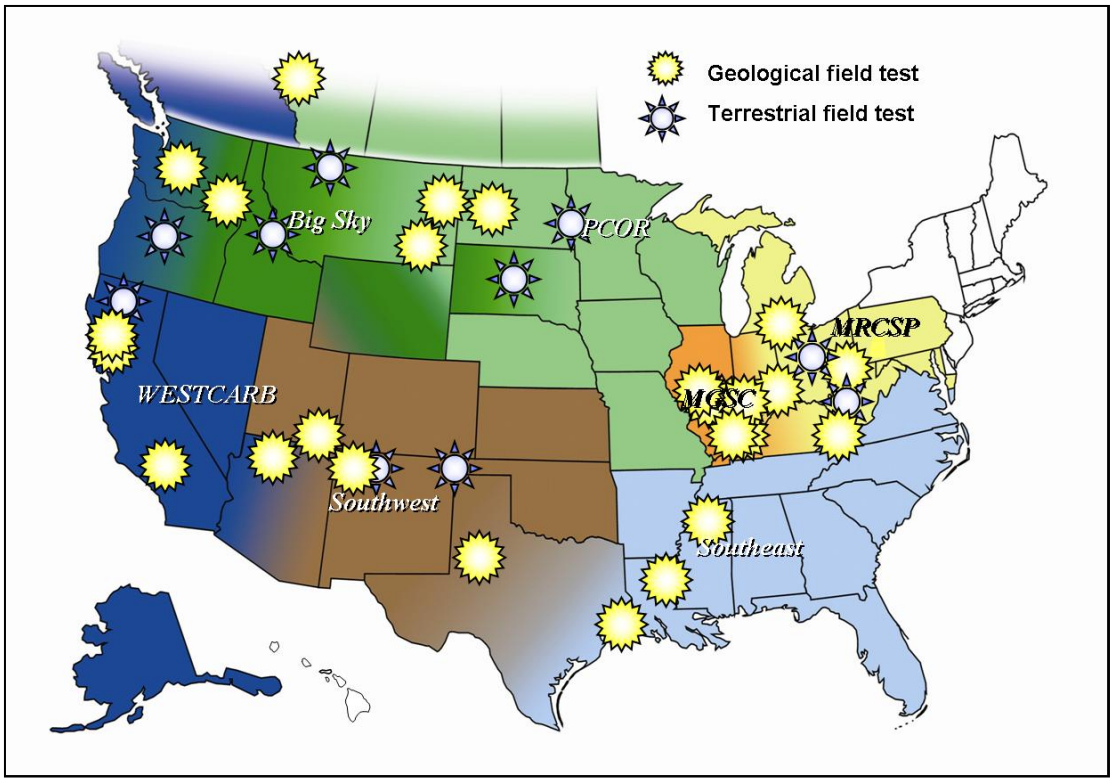

Figure 1 – Map showing the areas covered by the Regional Carbon Sequestration Partnerships and proposed field tests that will be undertaken to determine the best approaches to capture, storage and sequestration of greenhouse gases such as CO_2. Map from NETL (2006).

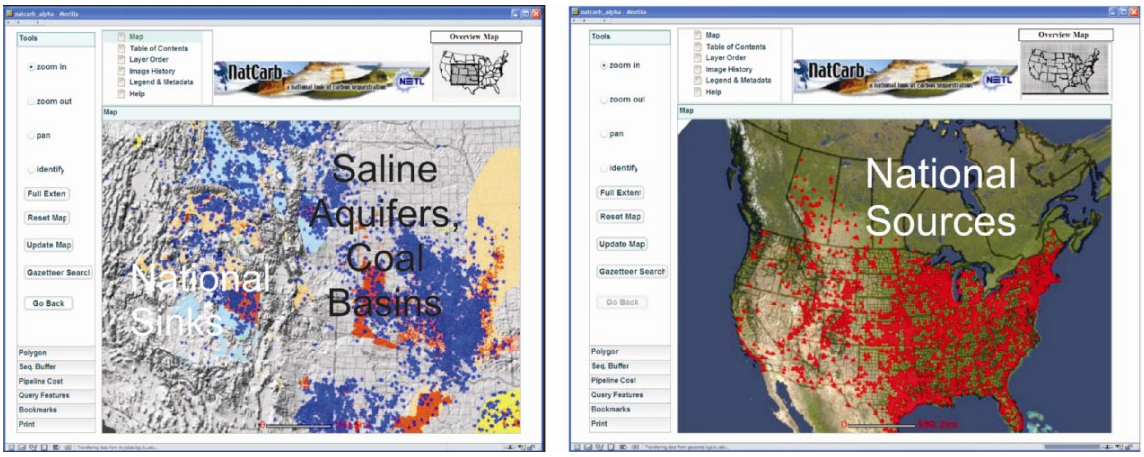

Figure 2 – NatCarb provides display and analysis of CO_2 sources (right) and potential sequestration sites (left) from the national to local scale (http://www.natcarb.org). Example shows all the large stationary sources of CO_2 across North America accessible through NatCarb and detailed image of potential CO_2 sequestration opportunities in saline formations and coal basins across the Mid-continent United States. Figures have backgrounds of digital elevation and physiographic backgrounds from remote publicly accessible servers.

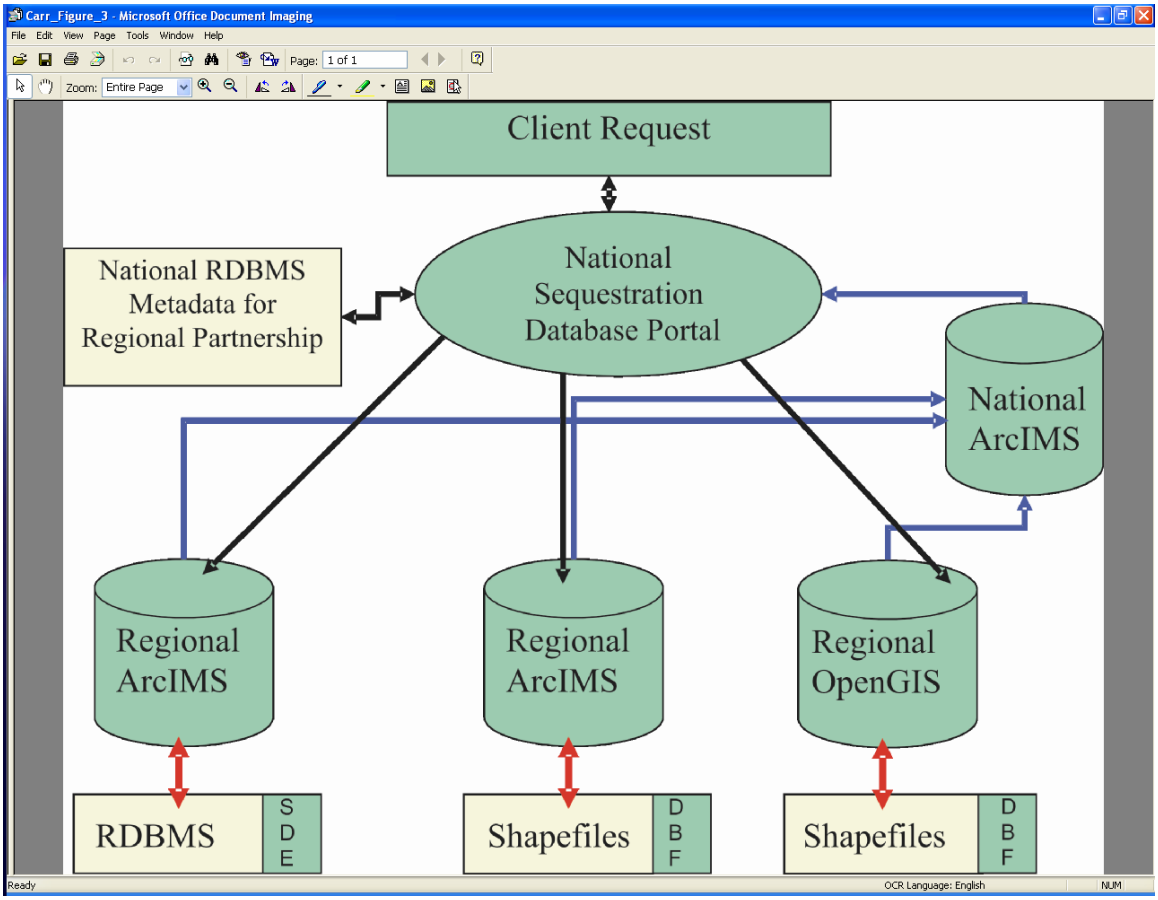

Figure 3 – NatCarb system structure links regional Internet Map Servers (ESRI's ArcIMS and OGC WMS 1.1.x) from the cooperating Carbon Sequestration Partnerships and other publicly accessible servers (e.g. EROS). Processing is undertaken on the regional servers and only the image is returned through the NatCarb portal. Data queries are also processed on regional servers and data is returned using XML.

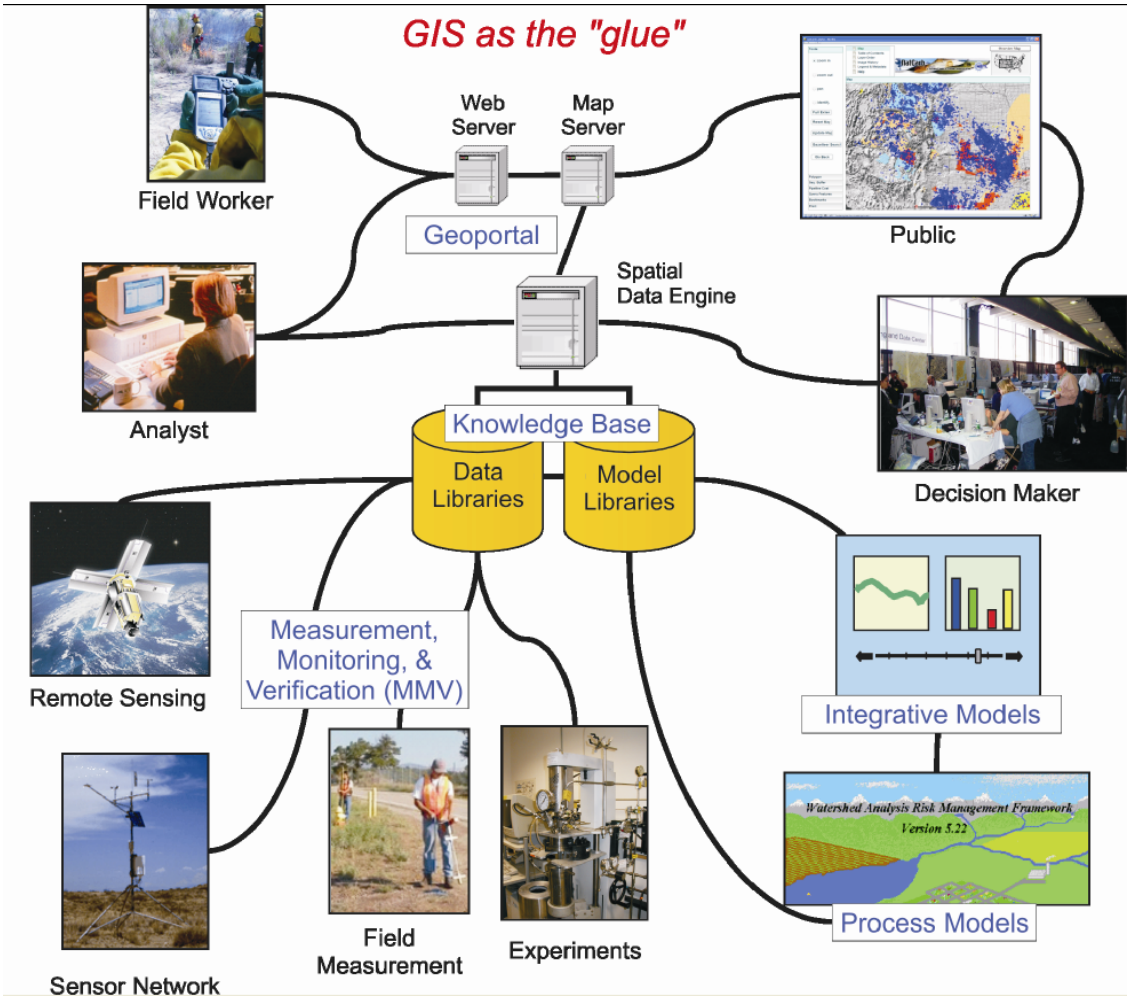

Figure 4 – Conceptual future **NatCarb** as it moves toward a *National Carbon Cyberinfrastructure (NCCI)* architecture consists of distributed computing solutions that are used to link acquisition of data and models into a distributed Knowledge Base across the partnerships and other publicly accessible servers (e.g., USGS, TerraServer) into a single system where data and models are maintained and enhanced by multiple managers at the local level, but are accessed and assembled through a single Web portal and provided to the decision-makers and the general public.

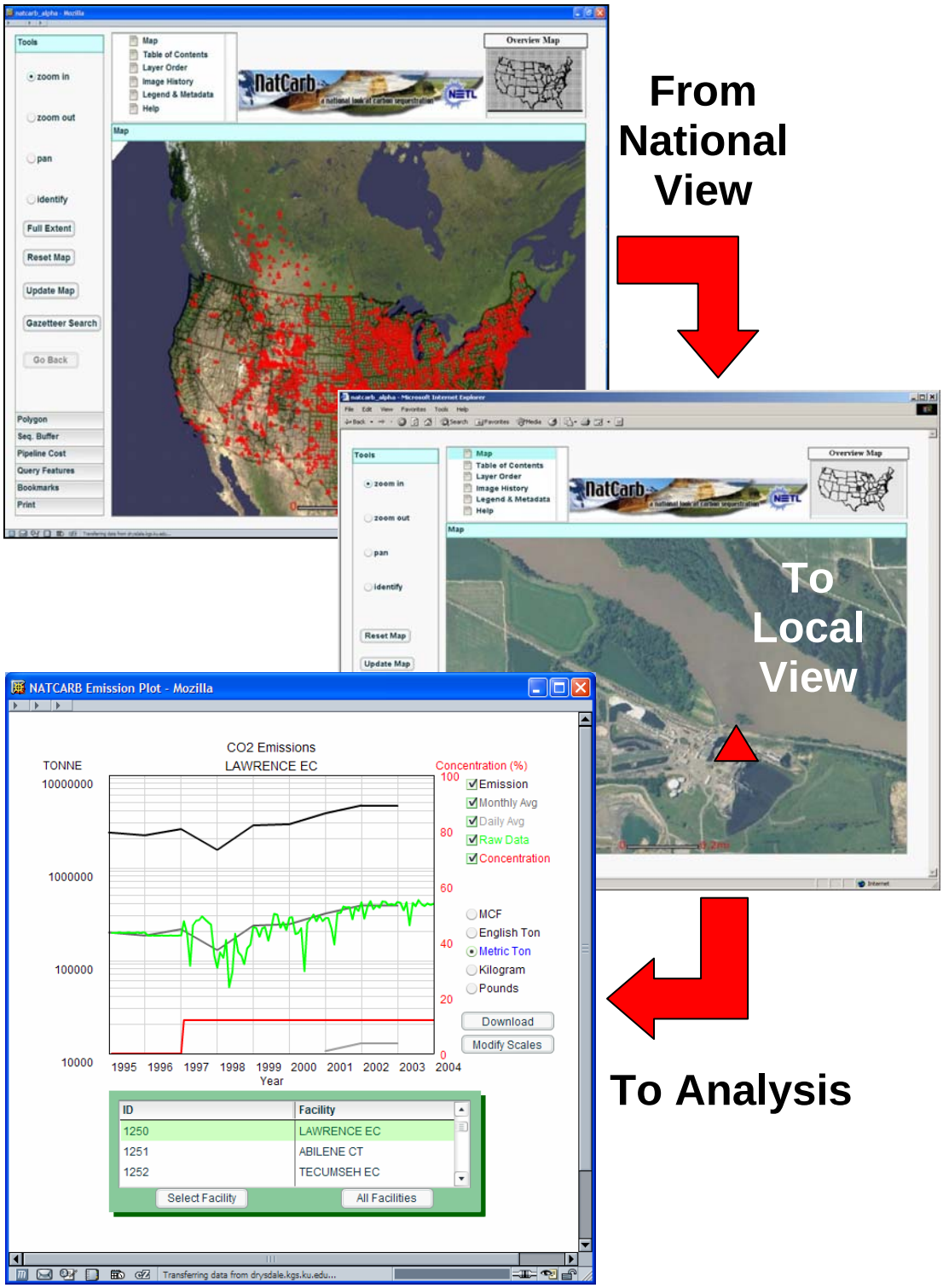

Figure 5 – NatCarb allows display and analysis of CO_2 sources and potential sequestration sites from the national to local scale (http://www.natcarb.org). Example shows all the large stationary sources of CO_2 across North America accessible through **NatCarb** and detailed image and display of CO_2 emissions from a single source.

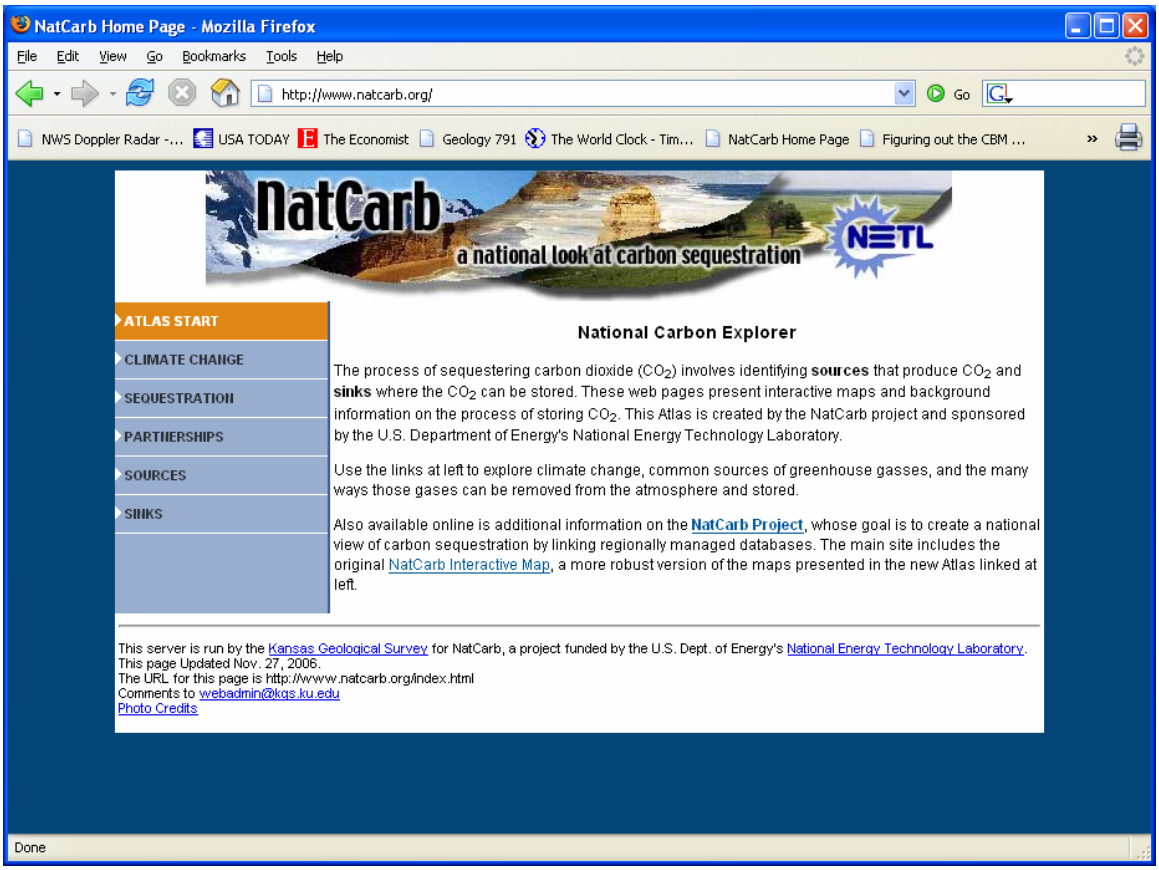

Figure 6 – Redesigned web page for **NatCarb**, which provides links to general information, the high-end "NatCarb Interactive Map" intended for the technical user, and to more general maps of CO_2 sources and potential sinks of the **Carbon Explorer** intended for a more general audience.

Figure 7 – Redesigned **NatCarb** web page for CO_2 sources providing links to static maps with high resolution graphics that can be downloaded and printed (Figure 10), and to interactive maps that can be customized and queried (Figure 9).

Figure 8 – Redesigned **NatCarb** web page for potential CO_2 storage sites providing links to static maps with high-resolution graphics that can be downloaded and printed and to interactive maps that can be customized and queried.

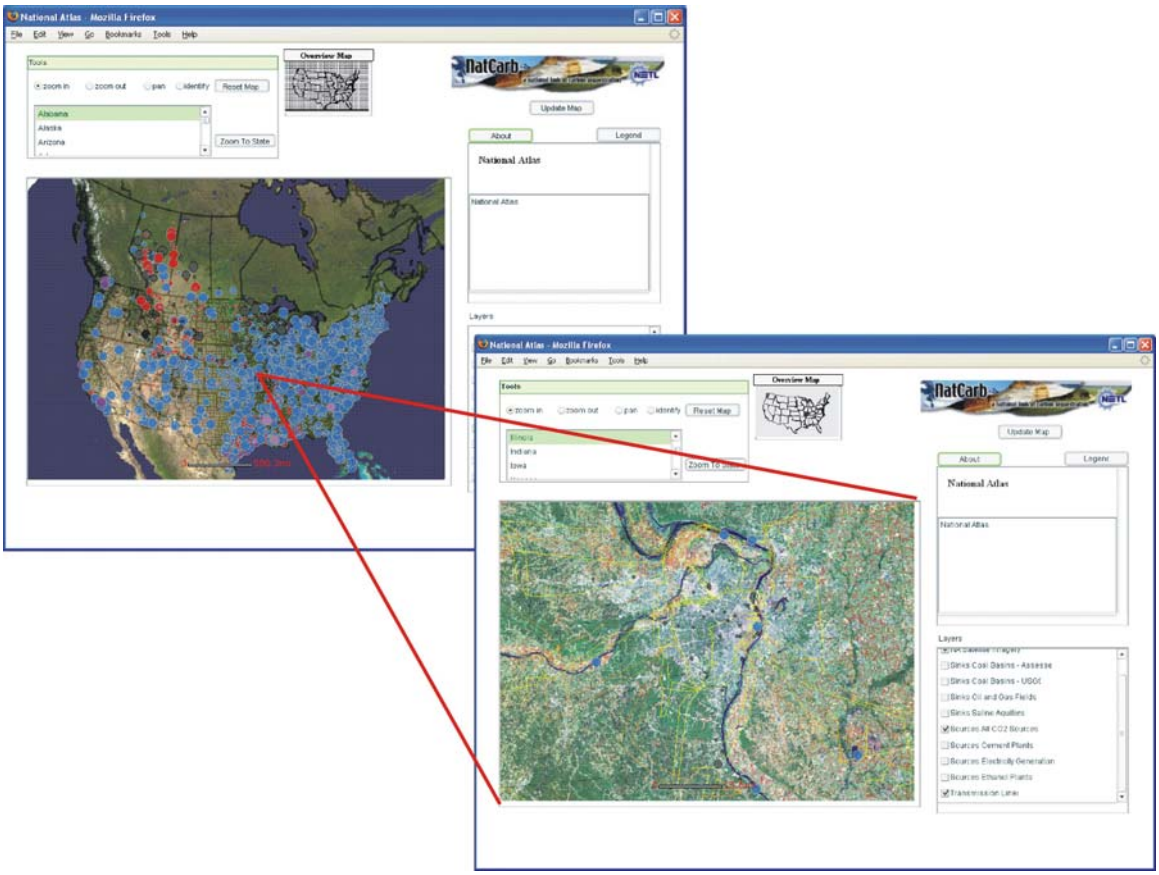

Figure 9 – Redesigned and simplified **NatCarb Carbon Explorer** ("**NatCarb** lite") interactive browser showing CO2 sources at the national level and ability to zoom into smaller areas such as St. Louis, Missouri. Also zoomed image is showing digital satellite image and location of major electrical transmission lines.

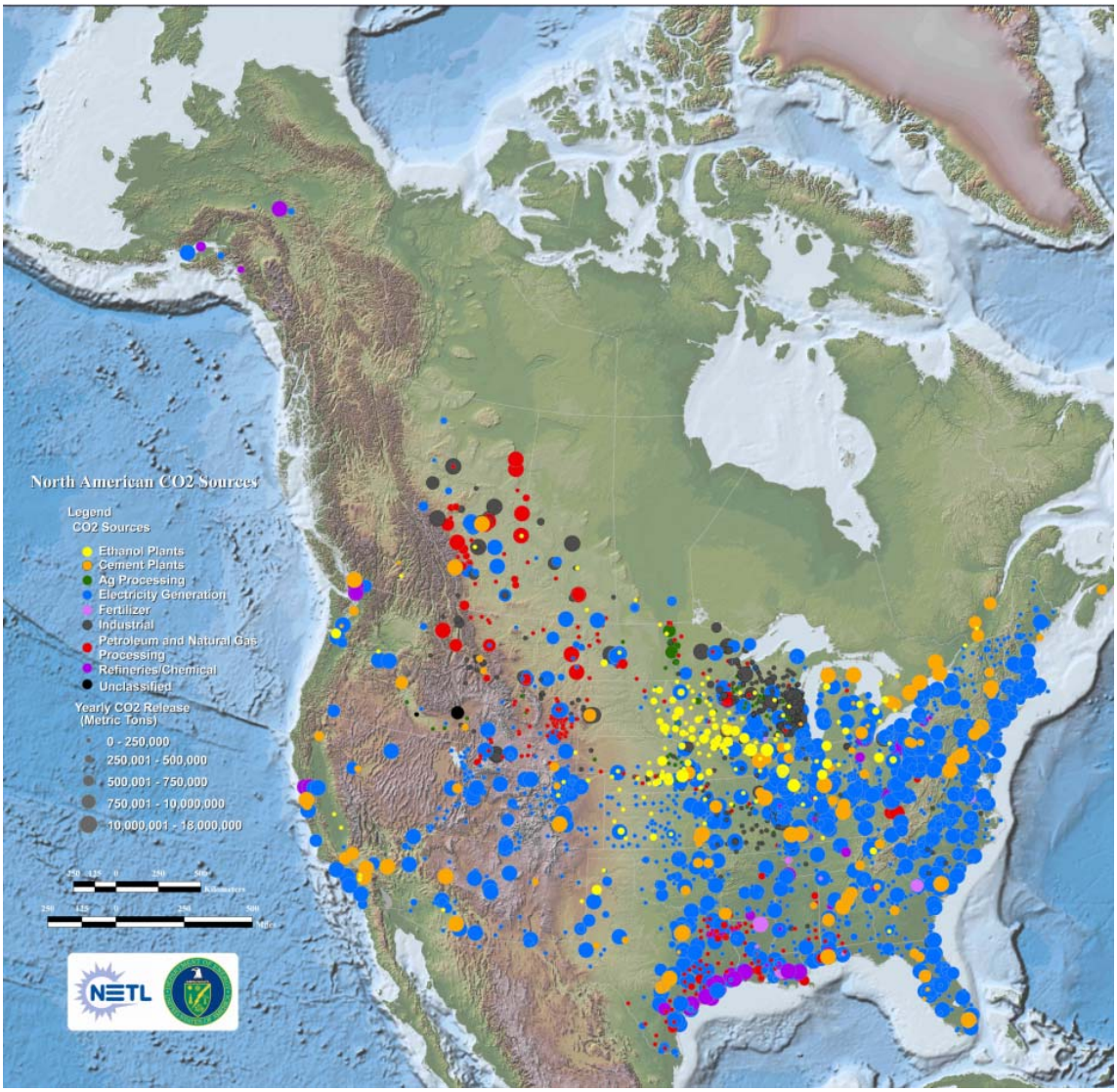

Figure 10 – Example of high resolution graphic static image from the **NatCarb** site showing the distribution of all CO_2 sources identified by the regional partnerships and served through **NatCarb**. Image can be downloaded and printed.

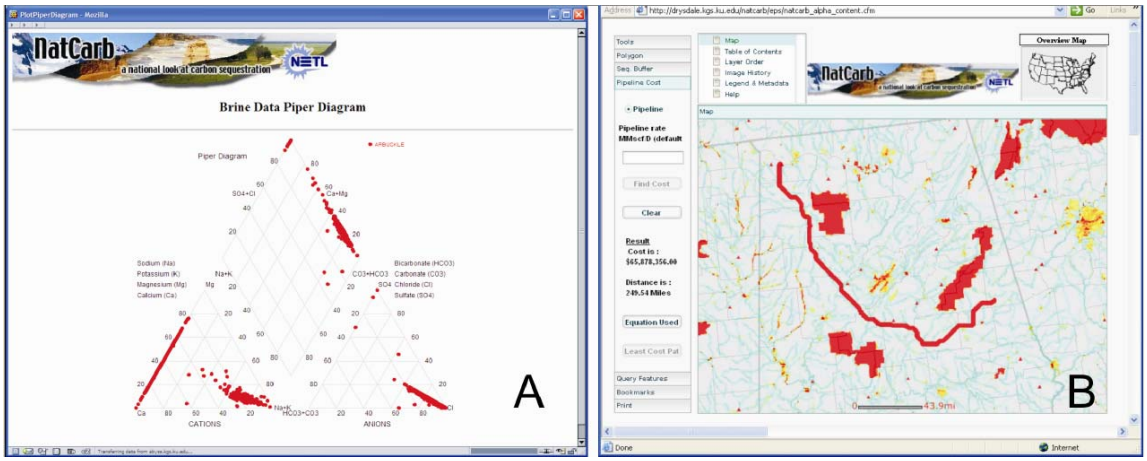

Figure 11 – Examples of tools and modeling capabilities being developed within the NatCarb geoportal. A) Example of a Piper Diagram tool for query and visualization of the geochemistry of brines in saline formations. In this example data is queried by formation across multiple states. B) Example of the pipeline model to select a route that minimizes cost base on digital elevation changes, river crossings and land use (e.g., urban areas and parks).

FUTURE WORK

The **NatCarb** group will continue to undertake the following tasks to integrate the Regional Carbon Sequestration Partnerships into a national CO_2 cyberinfrastructure. Tasks would include:

1) Improve the quality and coverage of the national carbon atlas that summarizes carbon sources and potential sinks. Work to provide tools to summarize data within the national CO_2 cyberinfrastructure at various geologic (e.g. basin) and geographic levels (e.g., state).
2) Provide an improved site for access by the general public to high quality information on all aspect of CO_2 capture and sequestration.
3) Work with the Regional Carbon Sequestration Partnerships to maintain and improve GIS layers and data covering all aspects of CO_2 sequestration. Provide expertise to integrate the institutions within a Partnership Region into a regional and national cyberinfrastructure of distributed geographic information and relational database management system (GIS/RDBMS). Work will continue to enhance, expand and integrate GIS layers and databases within and across regional partnerships. This approach would enable the regional partnerships to improve accessibility and consistency of approach among the regions.
4) Work with each regional center and each individual organization to develop and maintain the necessary expertise to fully develop a national CO_2 sequestration

cyberinfrastructure. We continue to provide system schema for each region and link to each region's system.

5) Provide improved access to national GIS layers maintained on our servers and through outside servers (e.g., USGS, EPA, USDA). If required in the future, provide data management on our system and serve data provided by a state, region or organization.

6) Maintain and improve access to all **NatCarb** information. Increase the performance of the **NatCarb** system through improved stability and speed, enhanced online tools for visualization, query and analysis, and increased integration of regional partnerships. Continue to incorporate advanced tools developed by other groups into **NatCarb** (e.g., MIT pipeline costing tool). Use the latest technology to maintain the **NatCarb** front-end access to map servers and databases. Provide improved management tools that assist the partnerships in loading, maintaining and enhancing GIS layers and databases, and decrease management overhead.

7) Continue to work to enhance the GIS and online capabilities of each regional partnership and develop online methods for submitting data to shared national databases. Provide tools to facilitate loading of data that has been supplemented by the Partnerships or NatCarb back to the originating organization.

8) Provide a workshop to facilitate communication amongst individuals working in the areas of geologic sequestration, public outreach and GIS. **NatCarb** can provide a leadership role in data management as applied to educating the

general public on carbon sequestration. We can share expertise beyond GIS and distributed databases. Improve the concept and the functionality of a federation of distributed resources (data and facilities) and distributed multidisciplinary expertise (Regional CO_2 Partnerships).

9) Work with various entities to improve and provide a national online coverage that details CO_2 emissions and sequestration for agricultural cropping rotations and field management practices in all USDA crop reporting districts/agricultural statistic districts in the continental United States, and for forestry practices.

10) Coordinate and work in close collaboration with other national and regional efforts and projects to develop improved scenarios and tools for carbon sequestration analysis. Work with national and regional experts on various technical aspects of cyberinfrastructure in order to provide a national system of the highest quality (e.g., MIT, Los Alamos National Lab, and San Diego Super Computer Center).

11) Continue to provide a series of updated lessons learned documents that document the challenges and rewards in the construction and maintenance of national distributed database systems. Provide access to software and procedures to construct a national CO_2 sequestration cyberinfrastructure. Provide periodic updates and presentations to NETL personnel, present results at national and international meetings pertinent to carbon sequestration and publish technical results in appropriate scientific and technical publications.

SUMMARY OF NatCarb SYSTEM

The **NatCarb** system provides analysis and display tools at various levels for different audiences. The general **NatCarb** browser provides the technical user with GIS experience the ability to query and display a large numbers of layers. The **NatCarb Explorer** is a simplified version that uses a limited number of layers and provides limited tools. **NatCarb Explorer** is intended for the general audience and policy makers. In both cases the data is the same and of two types:

- Map Layers
- Data Tables

Each data type is processed locally and served through the **NatCarb** server as an image or XML data page. Each partnership in the **NatCarb** Consortium is responsible for construction, enhancement, and maintaining the data for the particular region. **NatCarb** provides national databases covering geographic and subject areas not adequately covered by the partnerships (e.g., New England states and brine geochemistry). Data quantity is extremely large and constantly increasing. Numbers of records are in the many millions, involve over a century of anthropogenic activity, and cover a range of natural resource types (e.g., aquifers, to petroleum to coal). The data is extremely important to general natural resources and environmental questions in each Partnership. As a result, each Partnership has an interest in insuring the highest degree of quality control. However, with any extremely large, long-term and heterogeneous data set, individual data items can be incorrect. As a general activity of the institutions, the data is

undergoing constant quality control and enhancement. The **NatCarb** effort leverages the activities of the Regional CO_2 Partnerships.

In addition to data, **NatCarb** provides a number of display and analysis tools that can be used to manipulate and display the data. All the tools work across the entire **NatCarb** system and can be accessed through the **NatCarb** browser.

There are currently several hundred GIS layers that are stored on the five consortium servers. Data fall into the following categories:

- Agricultural
- Aquifer
- Base
- CO_2 Sources
- Coal
- Geology
- Petroleum
- Sequestration

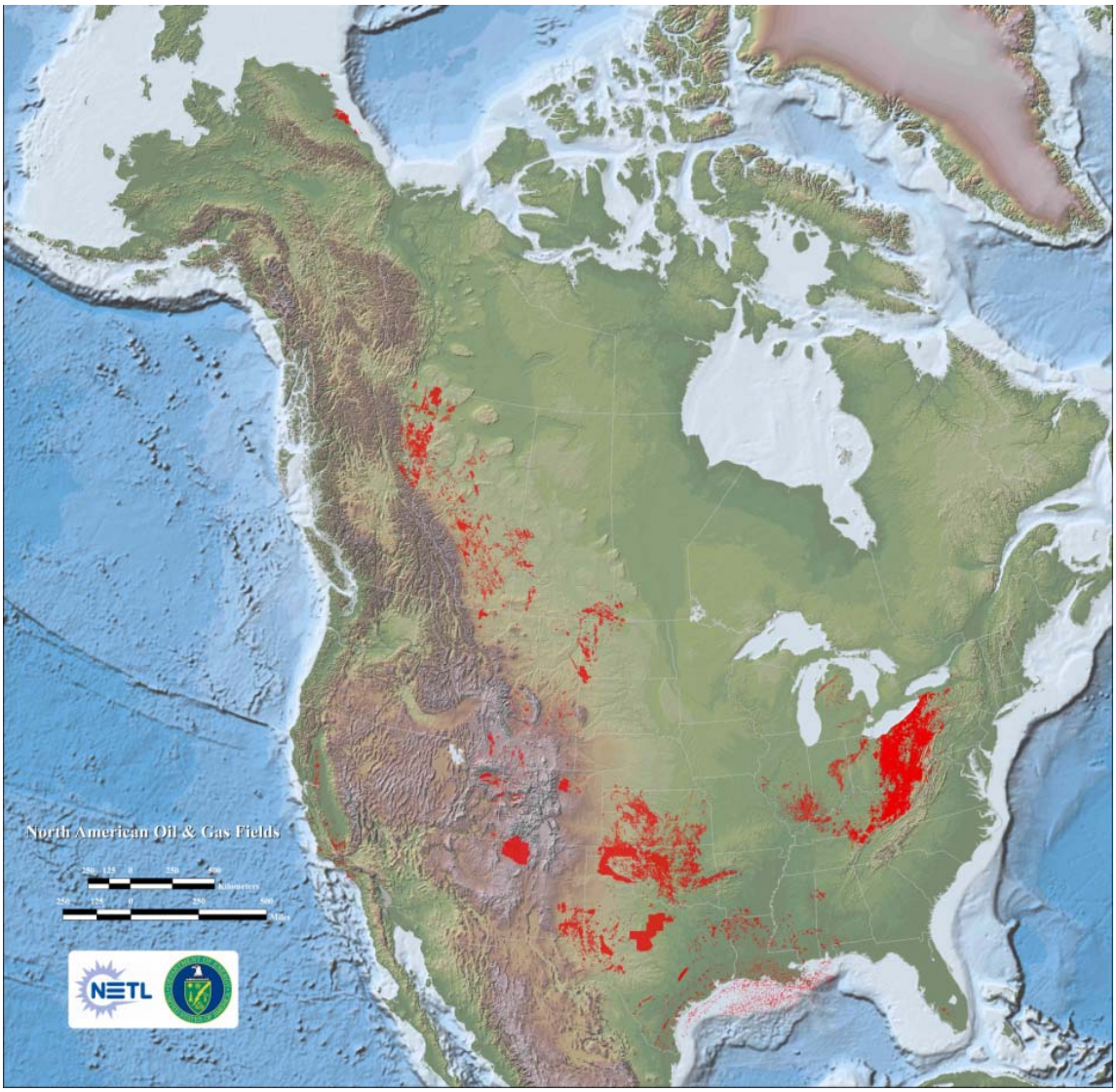

Figure 12 – Image showing distribution of oil and gas reservoirs that were evaluated by NETL's Regional Sequestration Partnerships and assembled through NatCarb. Oil and gas field outlines are available online or as hard copy images.

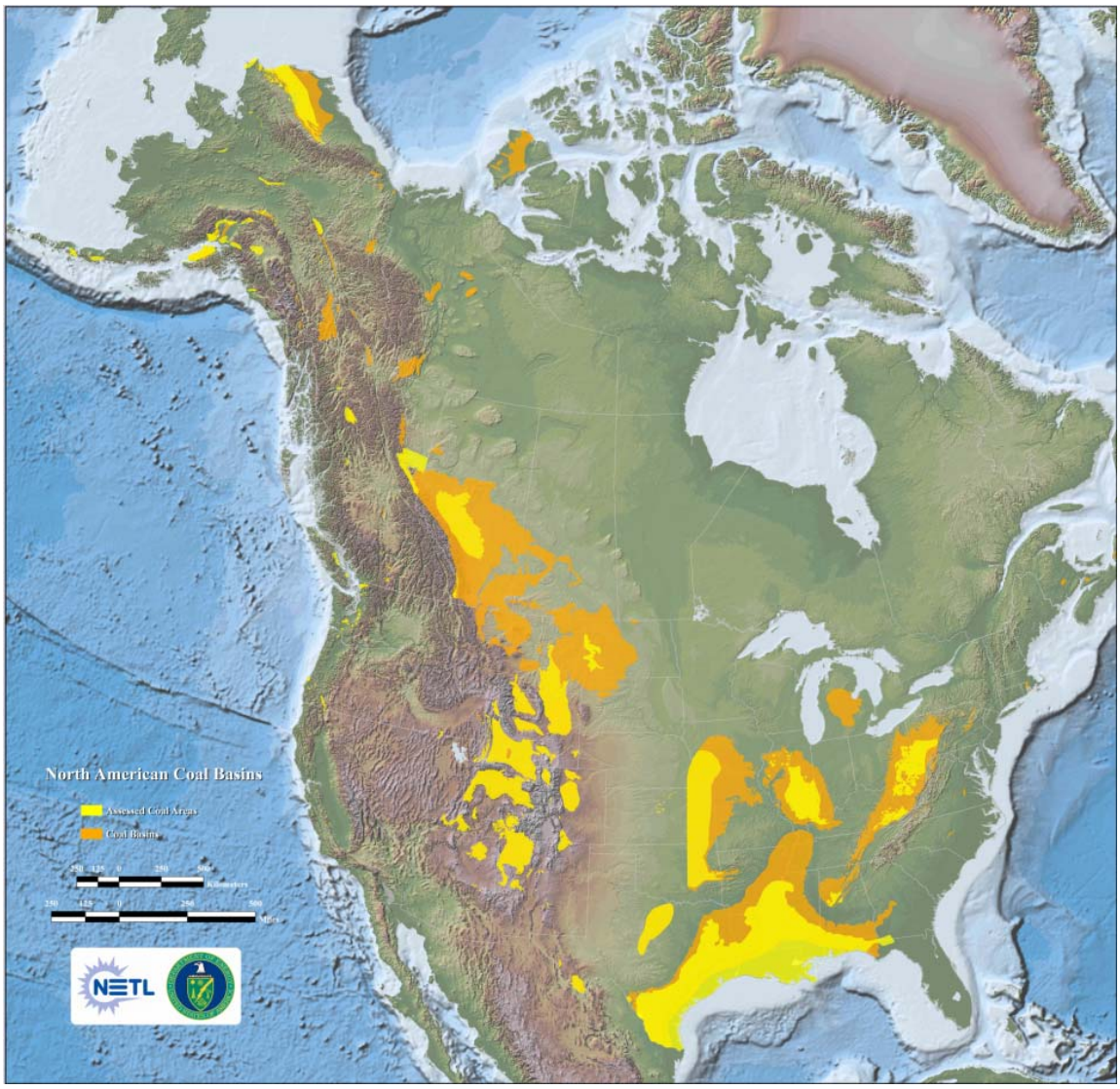

Figure 13 – Image showing distribution of basins containing coal beds (brown) and deep coal beds (yellow) that were evaluated by NETL's Regional Sequestration Partnerships and assembled through NatCarb. Basin outlines are available online or as hard copy images.

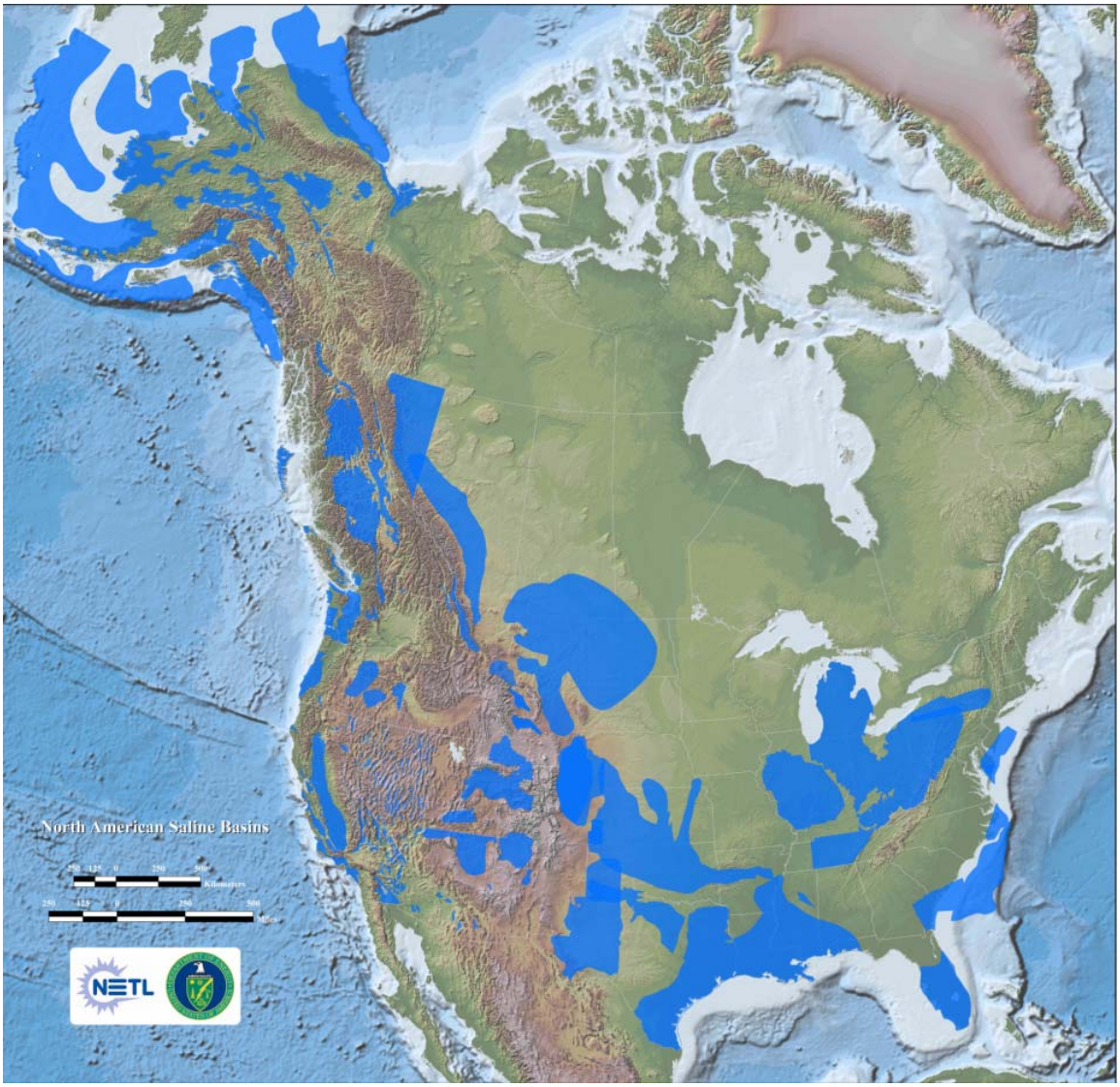

Figure 14 – Image showing distribution of basins containing saline formations that were evaluated by NETL's Regional Sequestration Partnerships and assembled through NatCarb. Basin outlines are available online or as hard copy images.

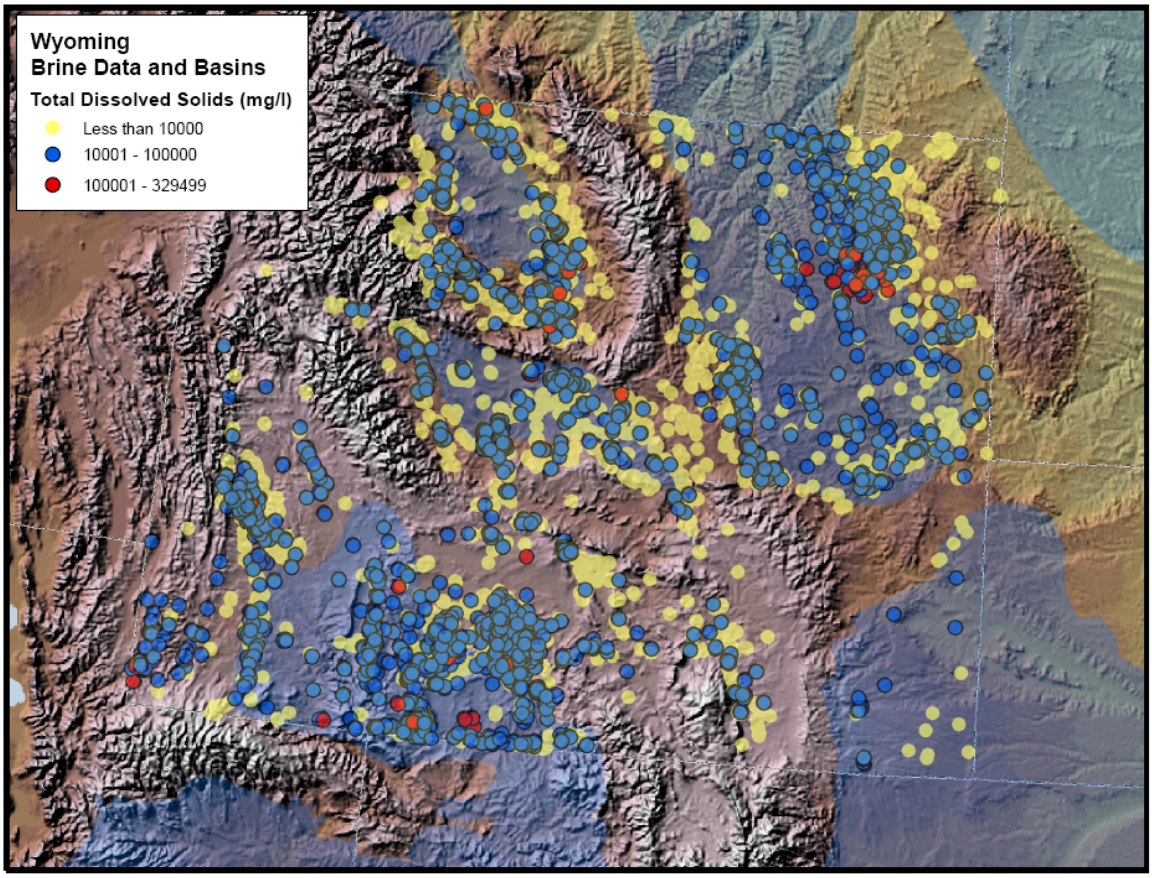

Figure 15 – Close-up image showing the distribution of locations in Wyoming with over 15,000 brine samples. Data is categorized by total dissolved solids (TDS). Samples with less than 10,000 mg/l TDS are legally considered potential potable water and need to be protected (yellow dots). Formations containing TDS concentrations above 10,000 mg/l are potential sites that merit further evaluation for potential CO2 storage (blue and red dots). Basins containing brine formations that have been evaluated are highlight in blue. Data on brine geochemistry can be accessed and summarized with several additional online tools. All data was assembled through NatCarb.

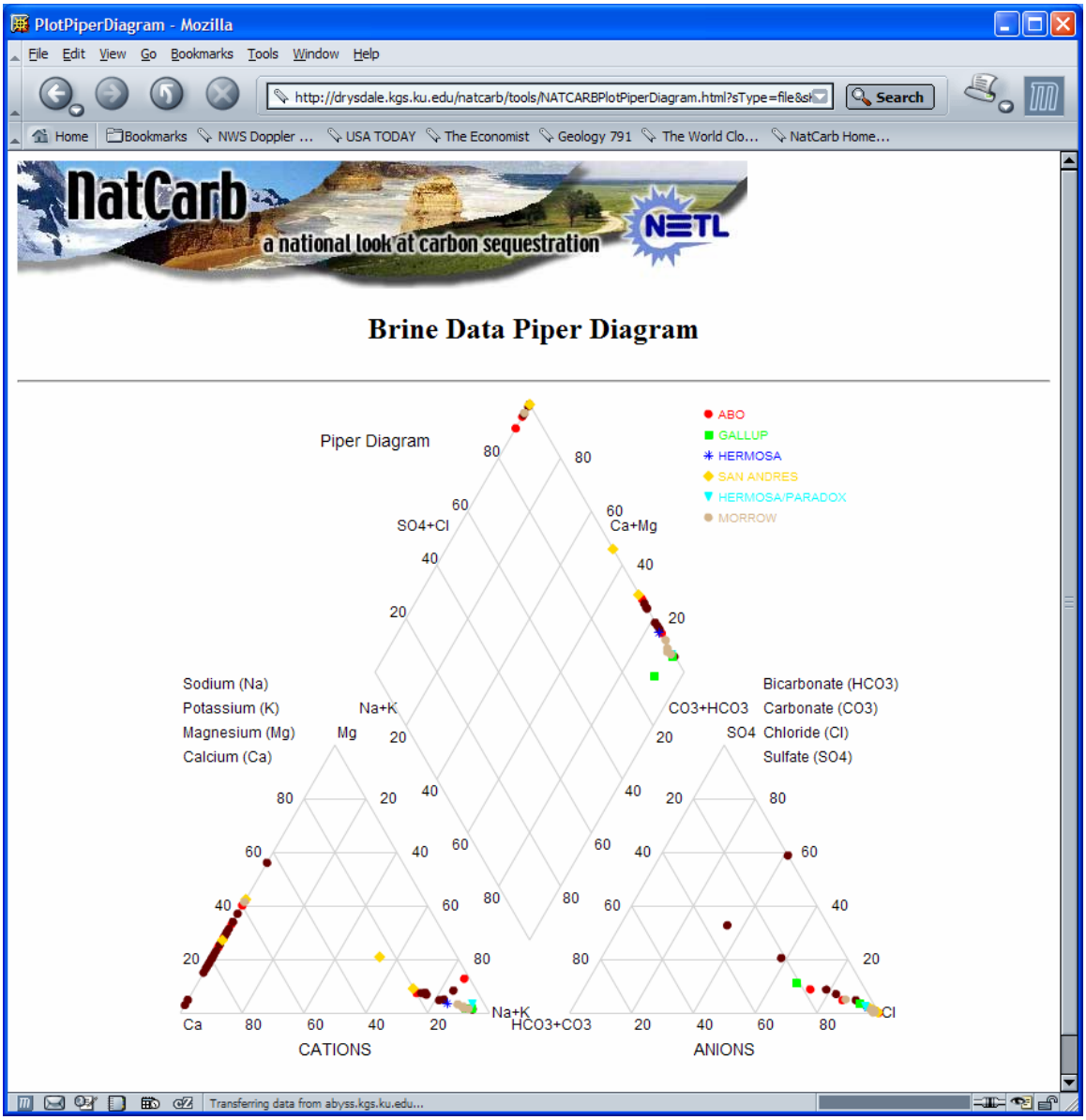

Figure 16 – Real-time Piper Diagram of selected brine samples from New Mexico showing variations in geochemistry among different saline formations. The ability to code samples by formation and other criteria (e.g., state or depth) is an improvement to the brine analysis tools.

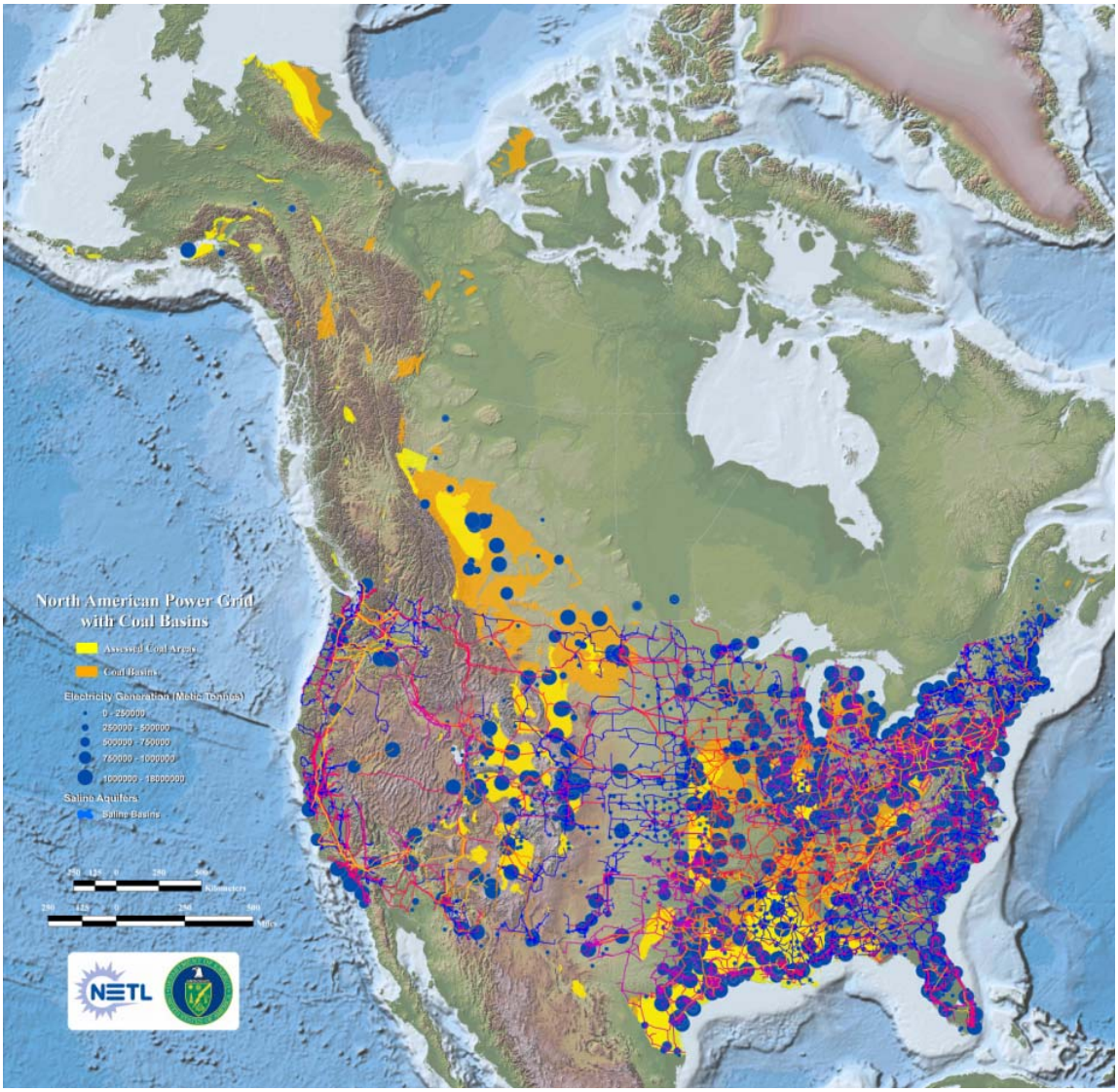

Figure 17 – Example custom image that can be generated from NatCarb provided map layers. Image shows distribution of CO_2 emissions from electric generation facilities and high voltage electric transmission lines that were evaluated by NETL's Regional Sequestration Partnerships and assembled through NatCarb.

NatCarb DATA MANAGEMENT TOOLS

As part of the **NatCarb** effort, tools were developed to provide complete distributed management of the system (i.e., data and GIS layers can be edited and loaded from anywhere in the **NatCarb** system). Management pages are provided by the **NatCarb** system to add, manage monitor the performance of layers from a remote server. The administrator at each of the Regional CO_2 Partnerships can manage individual servers and layers remotely, indicating which layers the site should allow users to view, which columns should be displayed or queried, and how to group the layers (Figure 3). Only this management information is stored in a relational database as metadata on the **NatCarb** server. Data processing is undertaken using models such brine analysis or pipeline routing stored on either the **NatCarb** server or the remote servers (Figure 4). All data remains on the local servers. The system can be monitored as to performance through a number of tabular and graphical tools.

TECHNOLOGY TRANSFER

The development of the **NatCarb** atlas is in itself a technology transfer activity, and will be ongoing from project initiation. The members of the consortium have been very active in presenting results in informal settings (e.g., presentation at District 7 of the Environmental Protection Agency, Energy and the Future [8/17/2006]). In addition, the following formal technology transfer activities have occurred during calendar year 2006:

1. Carr, Timothy R., K. D. Newell, J. G. Blencoe, S. Bhattacharya, Injection of Biogenic Landfill Gas into Coal Seams for Enhanced Coalbed Natural Gas Recovery and Carbon Sequestration, AAPG Annual Meeting – Houston, Texas, April, 9-12, 2006 http://aapg.confex.com/aapg/2006am/techprogram/A103317.htm
2. Carr, Timothy R., K. Look, J. Bartley, K. L. Hunsinger, Application of Large Online Data Sets for Improved Understanding of the Subsurface, AAPG Annual Meeting – Houston, Texas, April, 9-12, http://aapg.confex.com/aapg/2006am/techprogram/A103540.htm
3. Newell, K. D., T. R. Carr, Trends in Gas Content in Eastern Kansas Coals and Implications for Future Coalbed Natural Gas Exploration, AAPG Annual Meeting – Houston, Texas, April, 9-12, http://aapg.confex.com/aapg/2006am/techprogram/A103077.htm
4. Schurger, Stephen G., K. D. Newell, Timothy R. Carr, J. G. Blencoe: Integrated Subsurface Carbon Sequestration and Enhanced Coalbed Natural Gas Recovery Using Cement-Kiln Emissions, Wilson County, Kansas, AAPG Annual Meeting – Houston, Texas, April, 9-12, *(Best Poster Award from Energy Minerals Division – Also Student Paper)* http://aapg.confex.com/aapg/2006am/techprogram/A102390.htm
5. Carr, Timothy R., Paul M. Rich, Jeremy D. Bartley, and Gordon N. Keating, Carbon Cyberinfrastructure The Future of NatCarb, US Department of Energy's 5th Annual Conference on Carbon Sequestration, Alexandria, Virginia, May 8-10, Program with Abstract, CD proceedings.
6. Smith, Steven A, Timothy R. Carr, David W. Fischer, Jeremy D. Bartley, Wesley D. Peck, James A. Sorensen, Estimates of the Carbon Dioxide Sequestration Capacity for Lower Paleozoic Aquifer Systems in the Midcontinent Region of North America, , US Department of Energy's 5th Annual Conference on Carbon Sequestration, Alexandria, Virginia, May 8-10, Program with Abstract, CD proceedings.
7. Carr, Timothy R., Discussion Leader, Society Petroleum Engineers (SPE) Forum "Enhanced Oil Recovery – What's Next?" Broomfield, Colorado, June 26-29.

8. Carr, Timothy R., Paul M. Rich and Jeremy D. Bartley, The NatCarb Geoportal: Linking Distributed Data from the Carbon Sequestration Regional Partnerships, Journal of Map and Geography Libraries (Geoscapes), Special Issue on Department of Energy (DOE) Geospatial Science Innovations. (in press).
9. Carr, Timothy R., Models for Integrated Energy and Carbon Dioxide Sequestration Systems, Eastern Section AAPG Meeting, - Buffalo, New York, October 8-11, Program with Abstracts, p. 3, http://karl.nrcce.wvu.edu/esaapg/abstracts/2006abs.pdf

SUMMARY

The **NatCarb** project has been a successful venture in which funding from the National Energy Technology Laboratory (NETL) of the Department of Energy has been used to leverage natural resource knowledge and enhance the GIS expertise of the Regional Carbon Sequestration Partnerships. The Regional Carbon Sequestration Partnerships and NatCarb provide the first steps forward in development of a National Carbon Cyberinfrastructure (NCCI). **NatCarb** provides the critical information to policymakers, scientists, and engineers in the field of reduction of CO_2 emissions on sources, capture, transport, and storage of CO_2 within a geospatial local to continent-scale framework. A complete NCCI must also provide the information to discuss the costs, economic potential, and societal issues of CO_2 capture and storage, including public perception and regulatory aspects. Thus, a successful NCCI should provide the basis to evaluate the potential of CO_2 capture and storage, and provide strategies to mitigate economic costs and maximize environmental benefits. The future capture and storage of CO_2 will depend on a number of factors, including financial incentives provided for deployment, and whether the risks of storage can be successfully managed. However, a well designed NCCI can provide invaluable geospatial information at local to continent scales for scientific and technical personnel, policymakers in governments and environmental

organizations, and the interested concerned public to adequately address the complex issues of CO_2 capture and storage for mitigating future climate change

REFERENCES

Atkins, Daniel E., Kevin K. Droegemeier, Stuart I. Feldman, Hector Garcia-Molina, Michael L. Klein, David G. Messerschmitt, Paul Messina, Jerimiah P. Ostriker, and Margaret H. Wright. 2003. *Revolutionizing Science and Engineering through Cyberinfrastructure: Report of the National Science Foundation Blue-Ribbon Advisory Panel on Cyberinfrastructure*. National Science Foundation. http://www.nsf.gov/od/oci/reports/toc.jsp (accessed July 24, 2006).

Berman, Francine and Henry Brady. 2006. *Final Report: NSF SBE-CISE Workshop on Cyberinfrastructure and the Social Sciences*. National Science Foundation. http://vis.sdsc.edu/sbe/reports/SBE-CISE-FINAL.pdf (accessed December 13, 2006).

Beaumont, P., P.A. Longley, and D.J. Maguire. 2005. Geographic information portals--a UK perspective. *Computers, Environment, and Urban Systems* 29:49-69.

Dooley J.J, R. Dahowski, C. Davidson, M.A. Wise, N. Gupta, S.H. Kim, E.L. Malone. 2006. *Carbon Dioxide Capture and Geologic Storage: A core element of a Global Energy Technology Strategy to address climate change.* PNNL, Richland, WA. 37p. www.battelle.org/news/06/CCS_Climate_Change06.pdf (accessed December 13, 2006).

Edmonds, J., J. Clarke, J. Dooley, S. H. Kim, S. J. Smith. 2004. Stabilization of CO2 in a B2 World: Insights on the Roles of Carbon Capture and Disposal, Hydrogen, and Transportation Technologies. *Energy Economics*. 26(4): 517-537

Estrin, D., W. Michener, and G. Bonito. 2003. *Environmental cyberinfrastructure needs for distributed sensor networks. A Report from the National Science Foundation Sponsored Workshop, 12-14 August 2003*. La Jolla, CA: Scripps Institute of Oceanography. http://lternet.edu/sensor_report (accessed December 13, 2006).

Eswaran, H., E. Van den Berg, P. Reich and J.M. Kimble. 1995. Global soil carbon resources. pp. 27–43. *In* R. Lal, J.M. Kimble, E. Levine, and B.A. Stewart (eds.) *Soils and Global Change.* Boca Raton, FL: CRC/Lewis Publishers.

Goodchild, M.F., P. Fu, and P.M. Rich. 2006. Sharing geographic information: an assessment of the Geospatial One-Stop. *Annals of the Association for American Geographers*. In Press.

IOGCC. 2005. Carbon Capture and Storage: A Regulatory Framework for States. Prepared by Geological CO_2 Sequestration Task Force of the Interstate Oil and Gas Compact Commission, Bliss, K. J. (Coordinator). Oklahoma City: Interstate Oil and Gas Compact Commission. http://www.iogcc.state.ok.us/PDFS/CarbonCaptureandStorageReportandSummary.pdf (accessed July 24, 2006).

IPPC. 2005. IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.). New York: Cambridge University Press, http://arch.rivm.nl/env/int/ipcc/pages_media/SRCCS-

final/IPCCSpecialReportonCarbondioxideCaptureandStorage.htm (accessed July 24, 2006).

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science*. 304:1623-1627.

Maguire, D.J., and P.A. Longley. 2005. The emergence of geoportals and their role in spatial data infrastructures. *Computers, Environment, and Urban Systems* 29:3-15.

NETL 2006. DOE National Energy Technology Laboratory Website. http://www.netl.doe.gov/technologies/carbon_seq/partnerships/partnerships.html (accessed July 24, 2006).

Pacala, S., and Socolow, R. 2004. Stabilization wedge—solving the climate problem for the next 50 years with current technologies: *Science*, v. 305, p. 968–972.

Reeves, S. R. 2003. Assessment of CO2 Sequestration and ECBM Potential of U.S. Coalbeds, Topical report, US Department of Energy (DE-FC26-00NT40924). http://www.coal-seq.com/Proceedings2003/40924R07.pdf (accessed July 24, 2006).

UN. 1992. United Nations Framework Convention on Climate Change FCCC/INFORMAL/84 GE.05-62220 (E) 200705, List of Signatories & Ratification of the Convention Parties, http://unfccc.int/resource/conv/ratlist.pdf, Last updated 24 May 2004 (Accessed July 24, 2006).

US Environmental Protection Agency. 2006. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2004 (April 2006)**,** USEPA #430-R-06-002, http://www.epa.gov/climatechange/emissions/usinventoryreport.html, (accessed October 30, 2006).

Wigley, T.M.L., R. Richels., and J.A. Edmonds. 1996. Economic and environmental choices in the stabilization of atmospheric CO2 concentrations. *Nature*, 379(6562):240-243.

Zhang, Henry, Jeremy D. Bartley, Weifeng Li, Howard J. Herzog, Timothy R. Carr. 2006. A GIS-Based Model for CO2 Pipeline Transport and Source-Sink Matching Optimization, Fifth Annual Conference on Carbon Capture & Sequestration, May 8 - 11, 2006, Alexandria Virginia: www.carbonsq.com (accessed July 24, 2006).